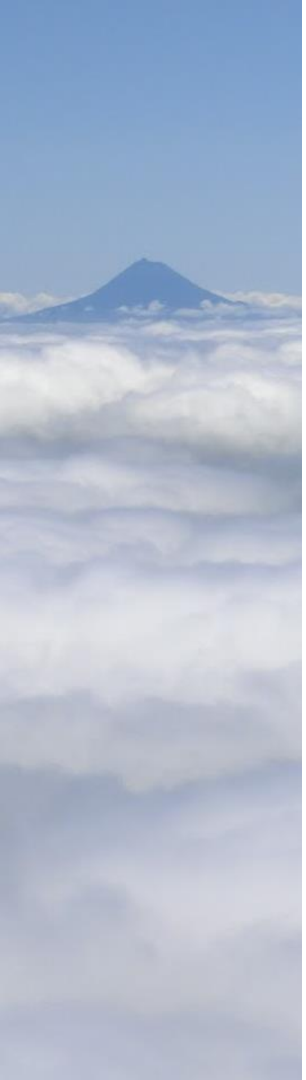


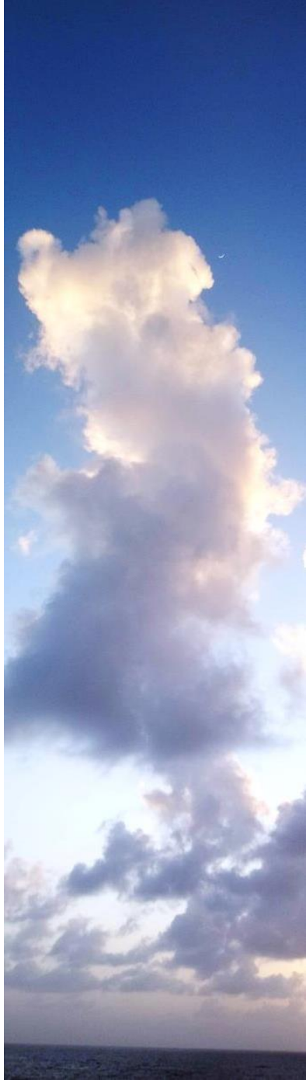
Turbulence properties in stratocumulus and cumulus clouds

Jakub L. Nowak

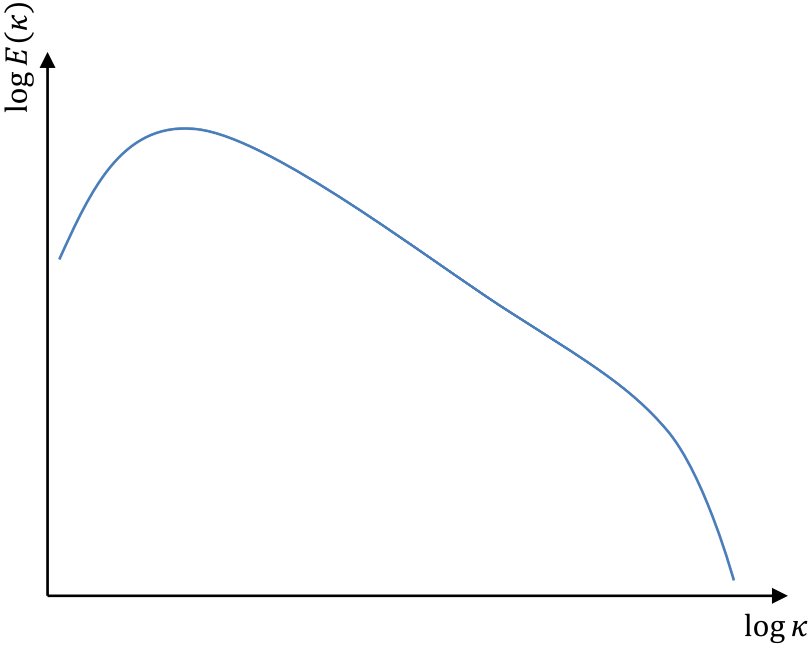
UNIVERSITY OF WARSAW | INSTITUTE OF GEOPHYSICS

Lille Turbulence Programme

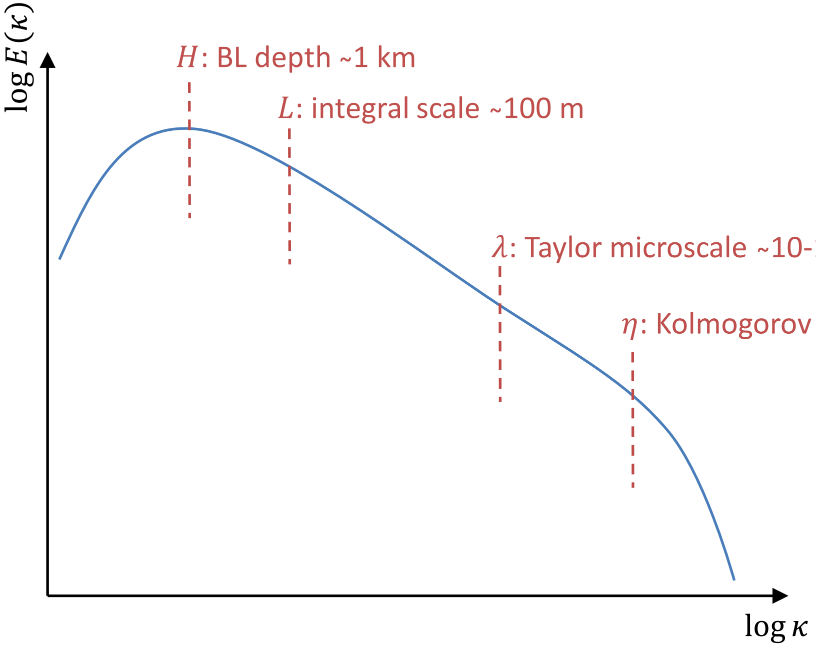
6.07.2023



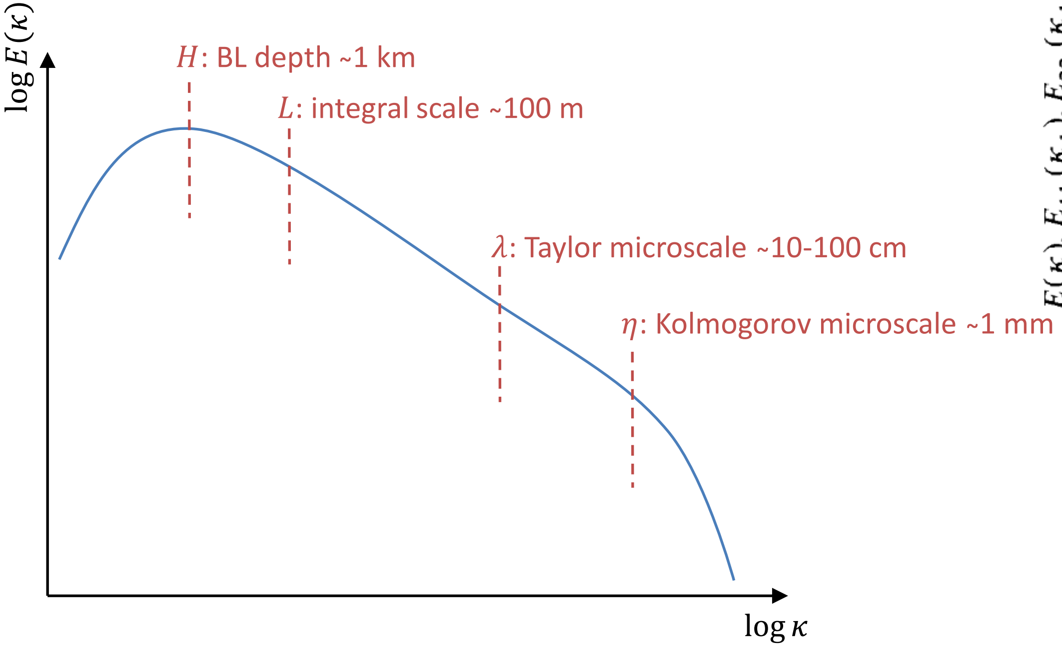
Turbulence cascade in atmospheric boundary layer

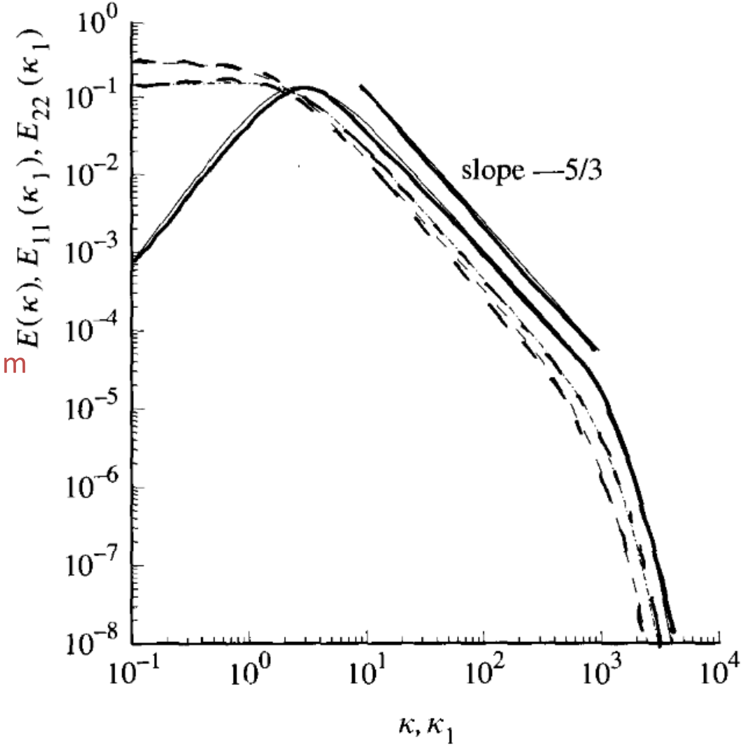


Turbulence cascade in atmospheric boundary layer



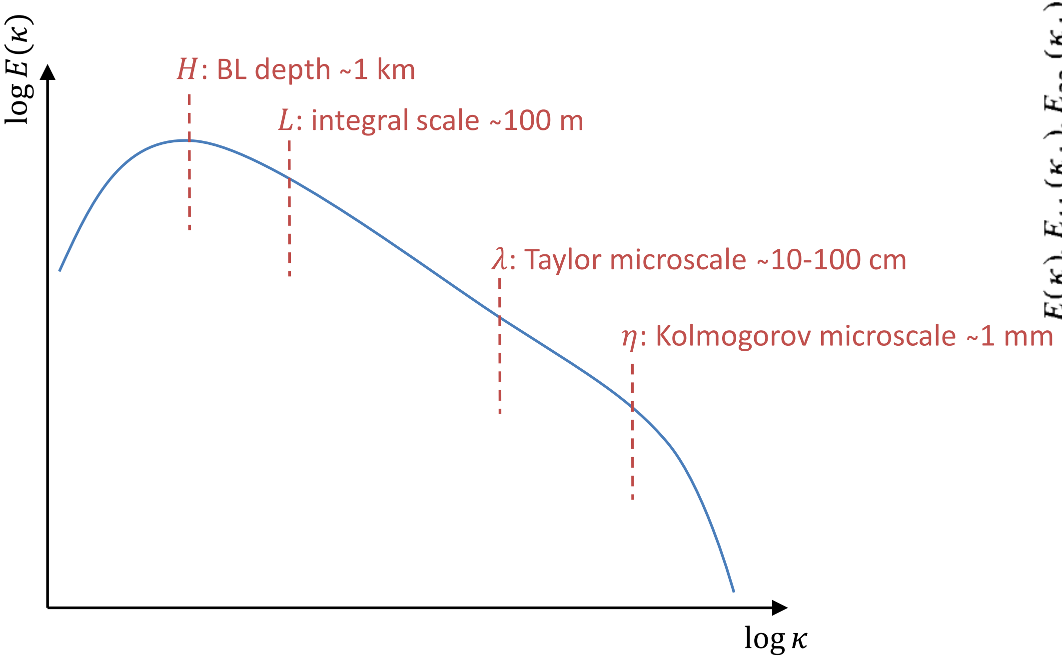
Turbulence cascade in atmospheric boundary layer

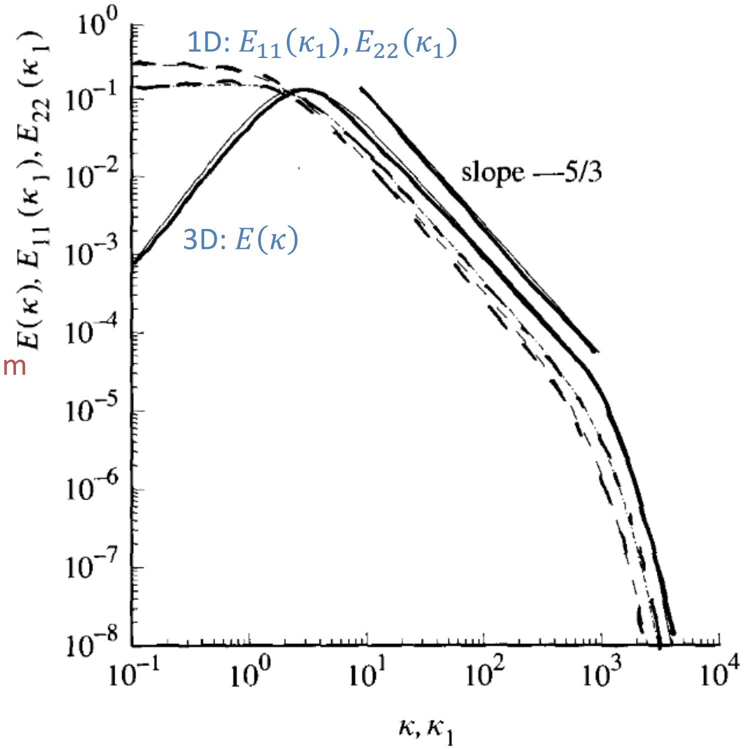




Pope 2000

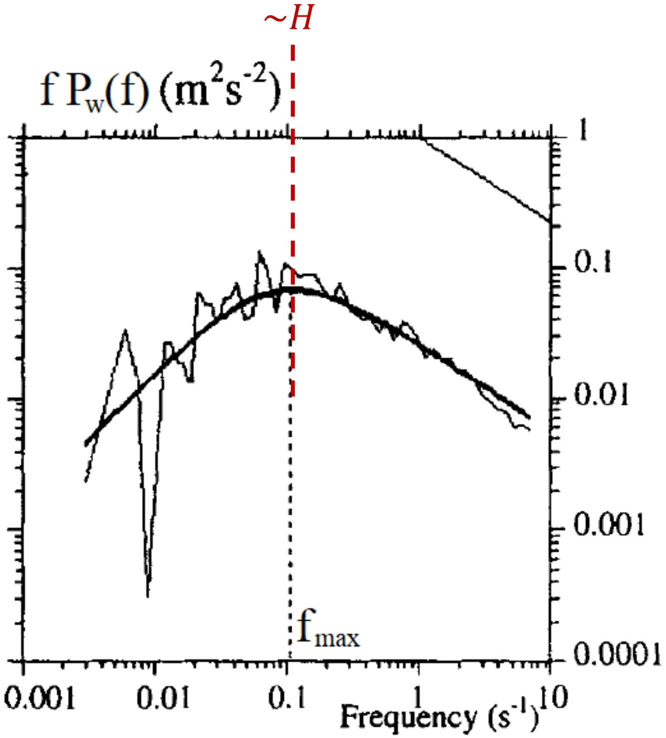
Turbulence cascade in atmospheric boundary layer



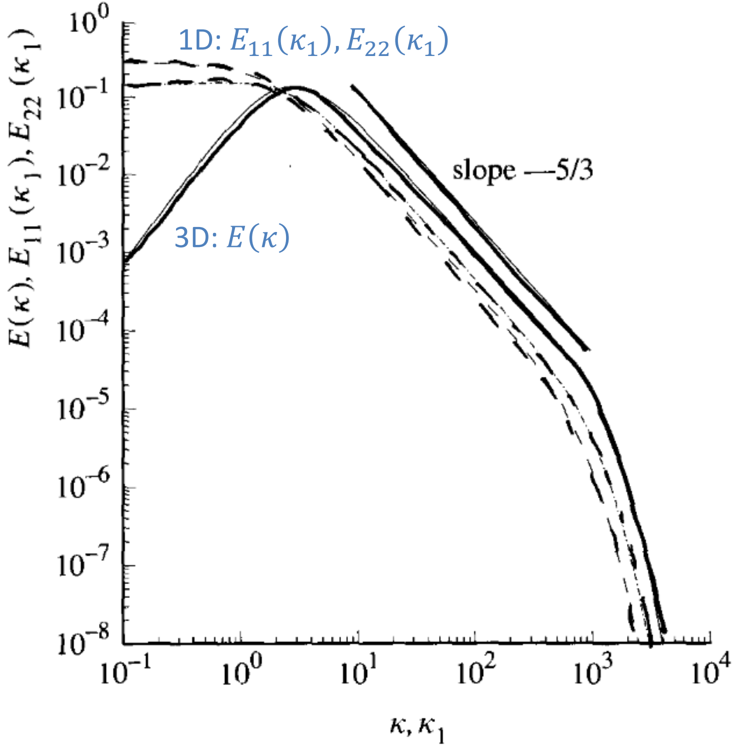


Pope 2000

Turbulence cascade in atmospheric boundary layer



Lambert and Durrand 1999

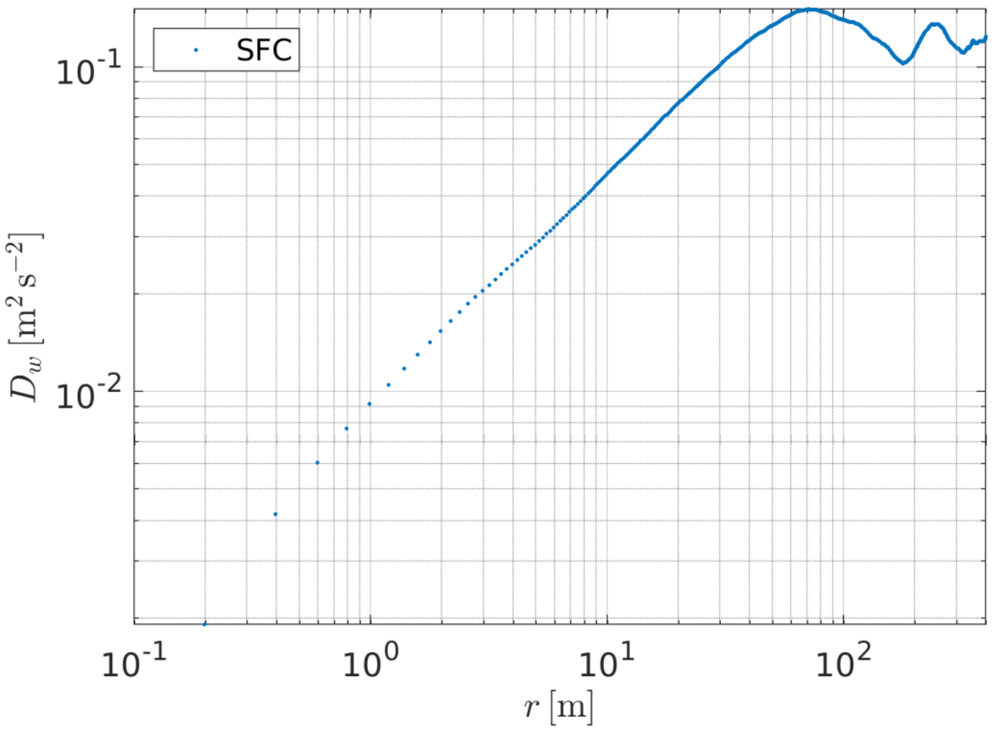


Pope 2000

Methods

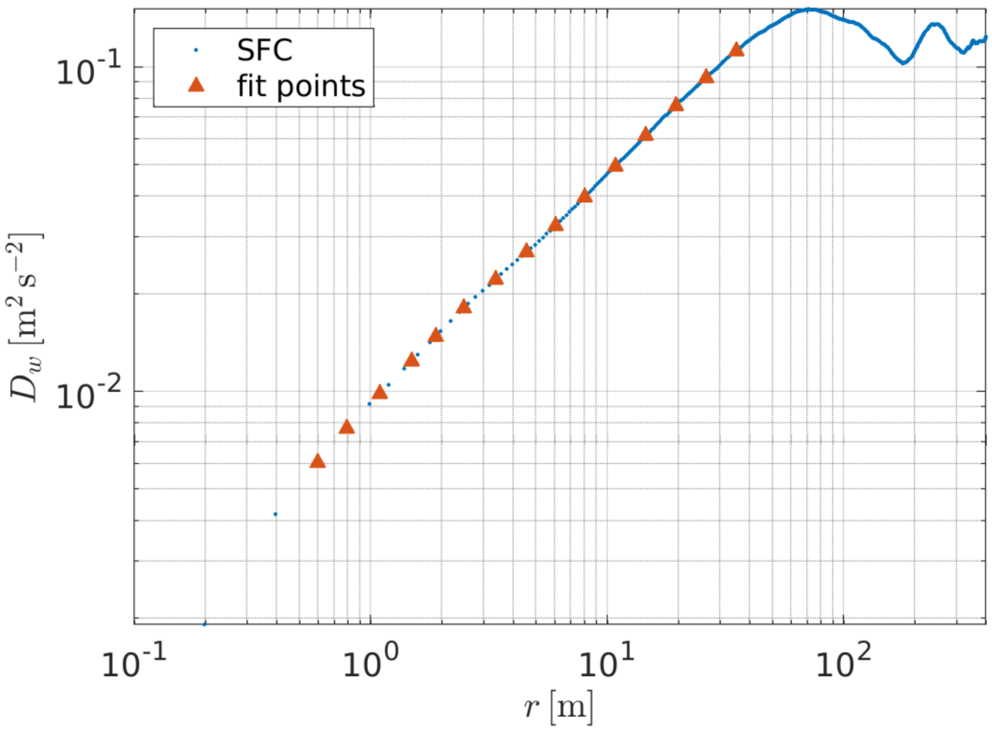
Nowak et al. 2021

Methods



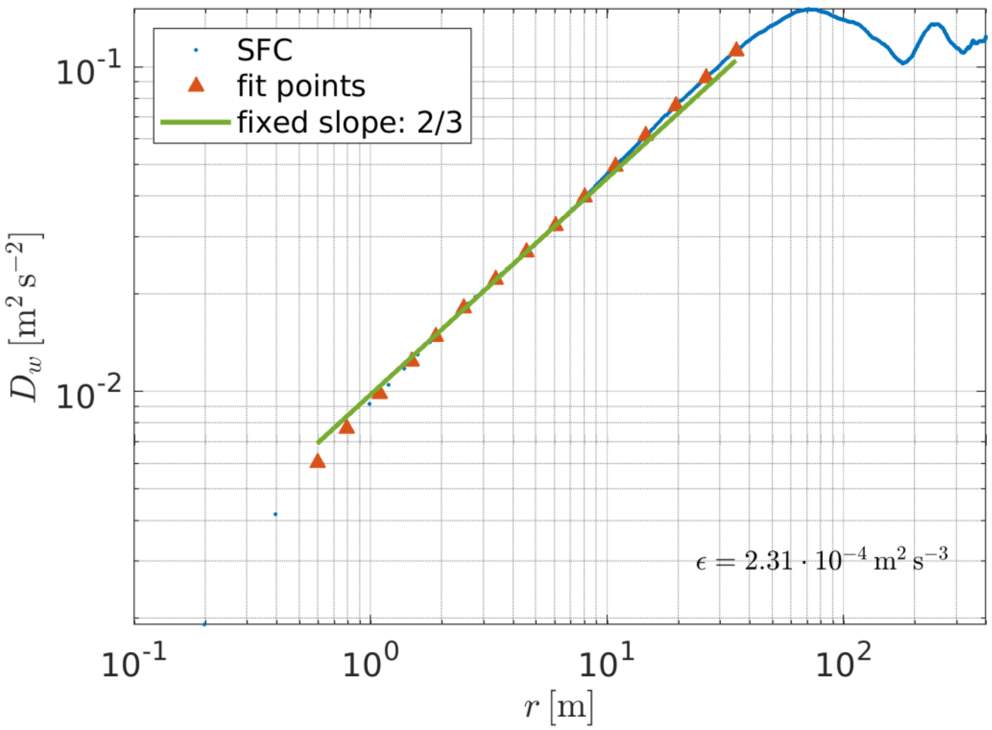
Nowak et al. 2021

Methods



Nowak et al. 2021

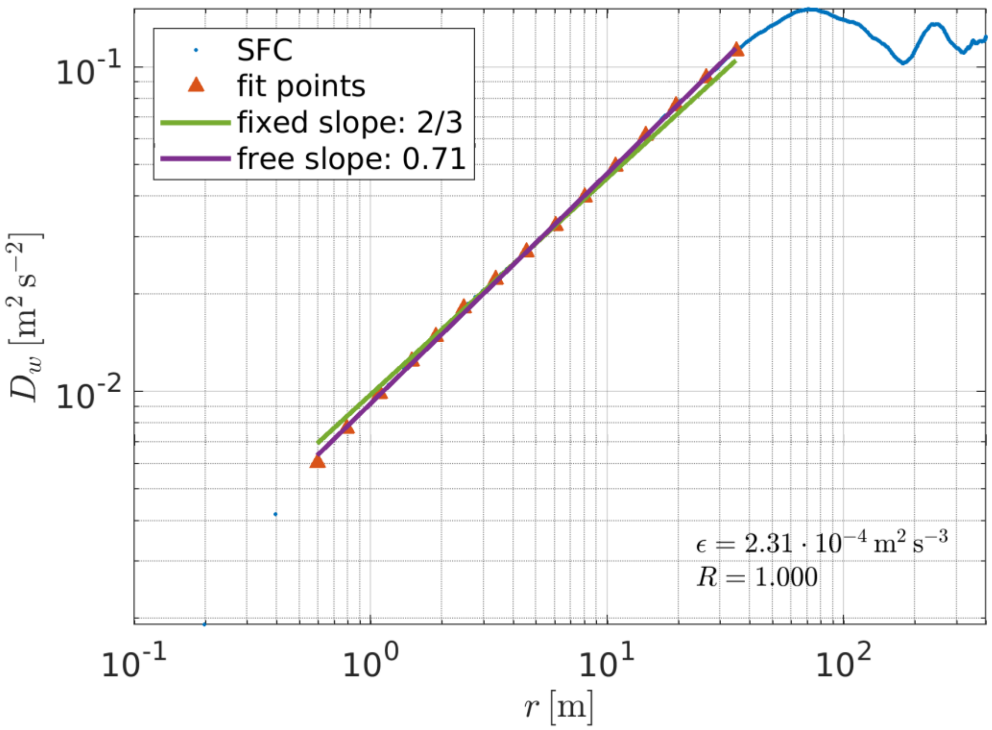
Methods



Epsilon fit $D_w(r) = B_T(\epsilon_w r)^{\frac{2}{3}}$

Nowak et al. 2021

Methods

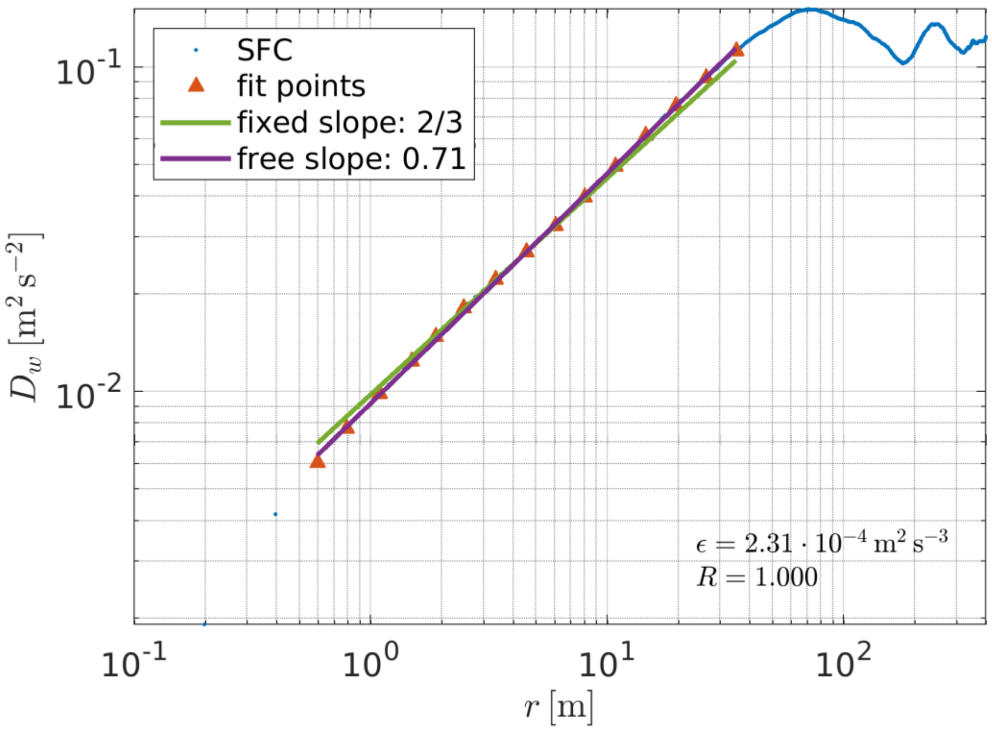


Epsilon fit $D_w(r) = B_T(\epsilon_w r)^{\frac{2}{3}}$

Scaling fit $D_w(r) = \mathrm{const}\, r^{s_w}$

Nowak et al. 2021

Methods



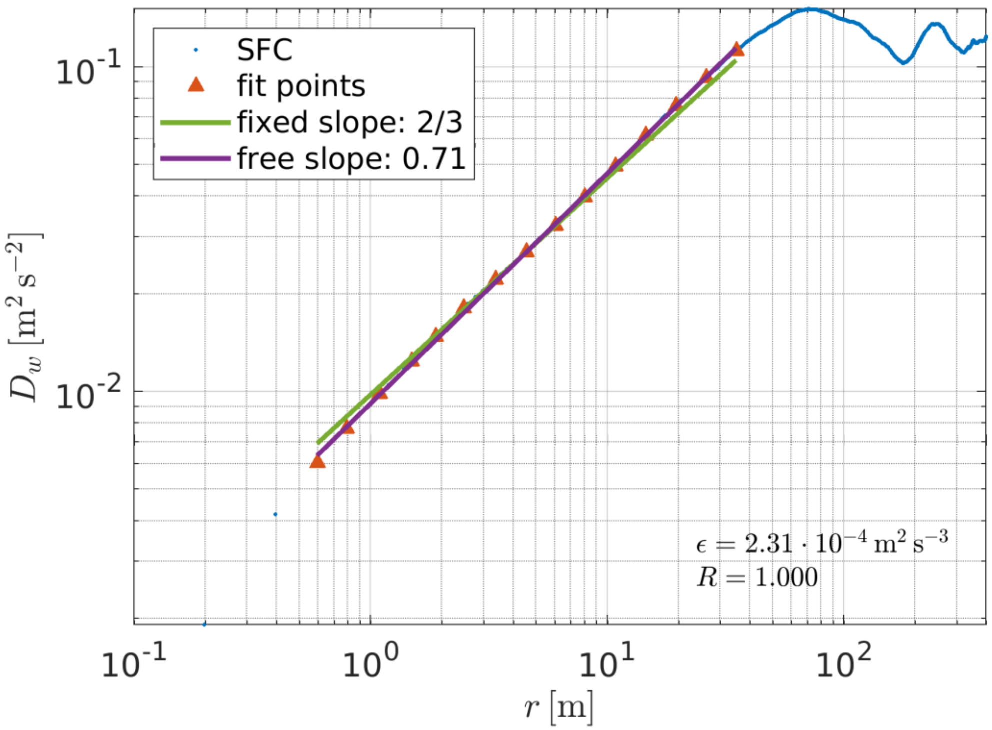
Epsilon fit $D_w(r) = B_T(\epsilon_w r)^{\frac{2}{3}}$

Scaling fit $D_w(r) = \mathrm{const}\, r^{s_w}$

Correlation $R_w(\log r, \log D_w)$

Nowak et al. 2021

Methods



Nowak et al. 2021

Epsilon fit $D_w(r) = B_T(\epsilon_w r)^{\frac{2}{3}}$

Scaling fit $D_w(r) = \mathrm{const}\, r^{s_w}$

Correlation $R_w(\log r\,, \log D_w)$

Isotropy

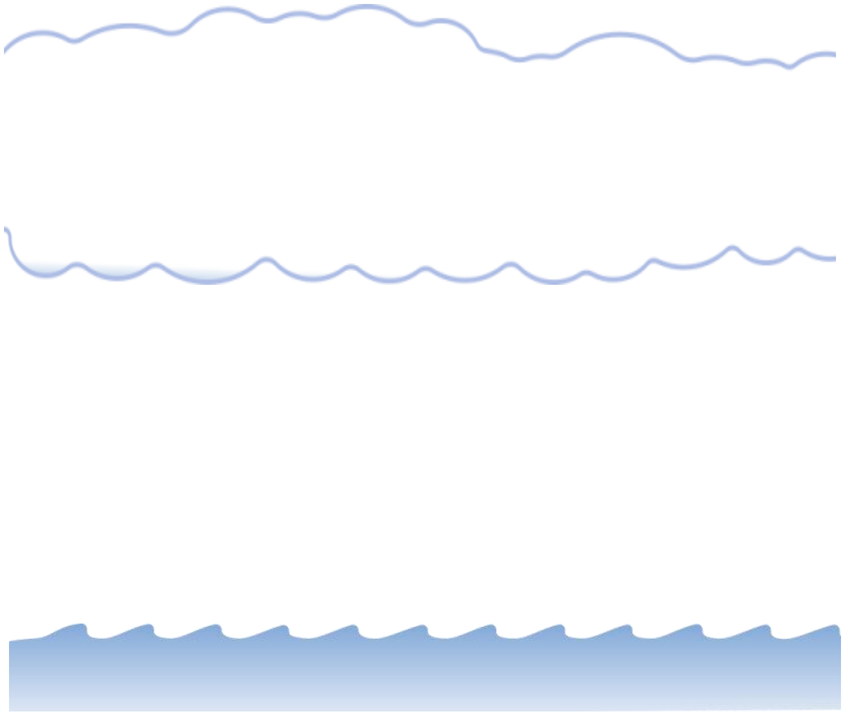
$$\langle u'^2\rangle = \langle v'^2\rangle = \langle w'^2\rangle \quad \epsilon_u = \epsilon_v = \epsilon_w$$

Anisotropy

$$A_{var} = \frac{2\langle w'^2\rangle}{\langle u'^2\rangle + \langle v'^2\rangle} \neq 1$$

$$A_\epsilon = \sqrt{\frac{2\epsilon_w^2}{\epsilon_u^2 + \epsilon_v^2}} \neq 1$$

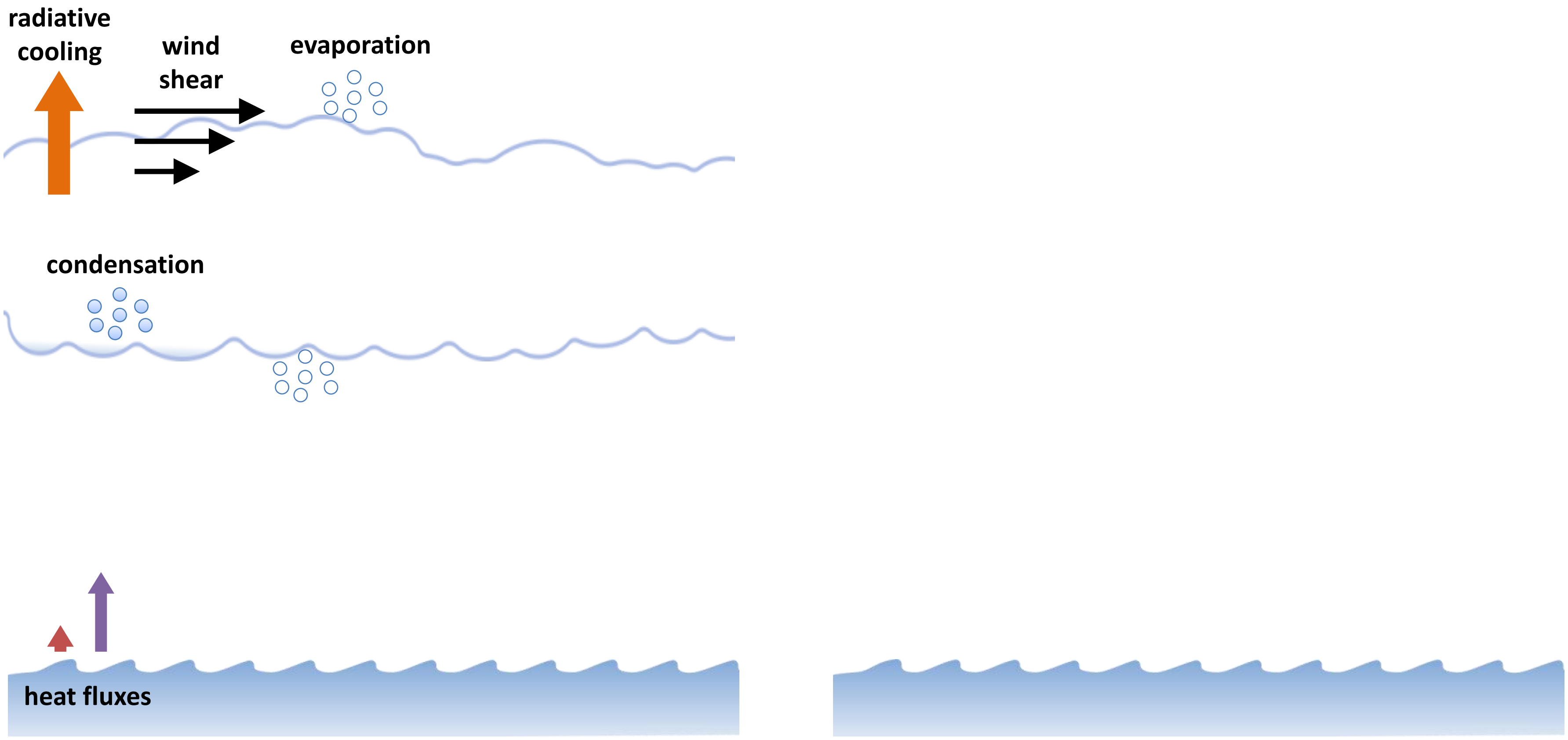
Subtropical regimes of atmospheric boundary layer



Stratocumulus-topped BL

Shallow cumulus BL

Subtropical regimes of atmospheric boundary layer



Stratocumulus-topped BL

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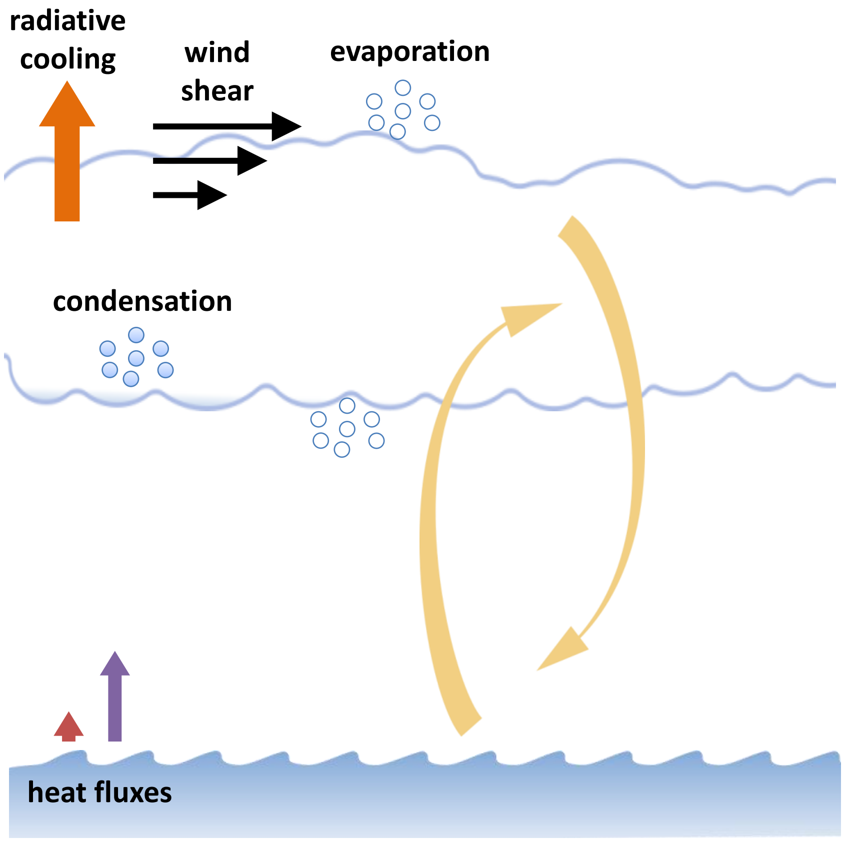
Subtropical regimes of atmospheric boundary layer



Stratocumulus-topped BL

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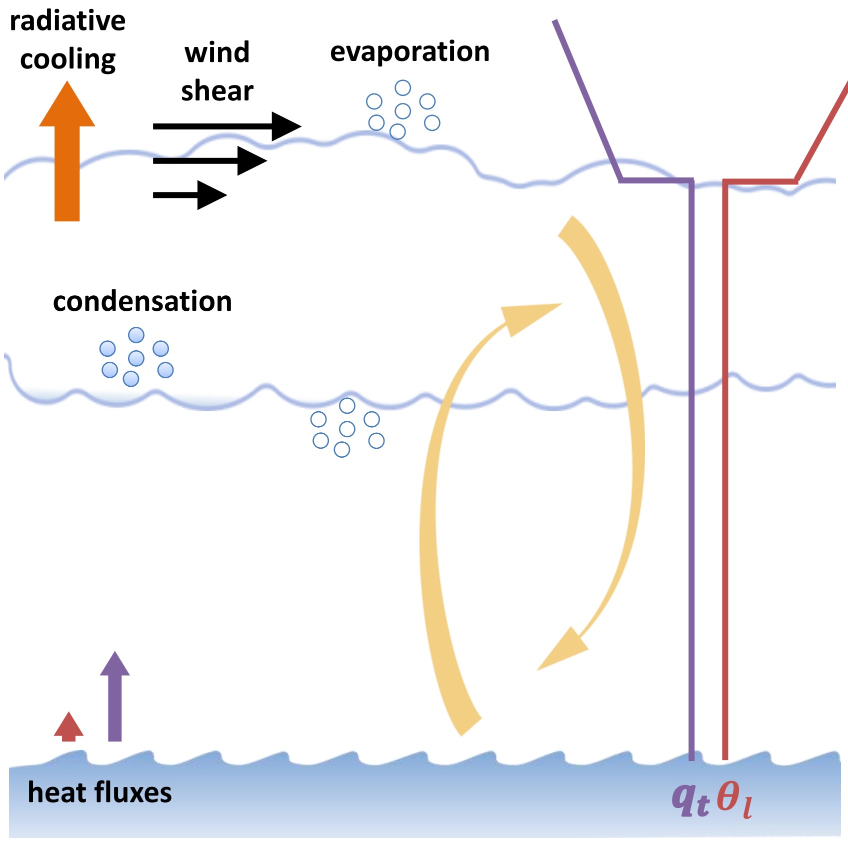
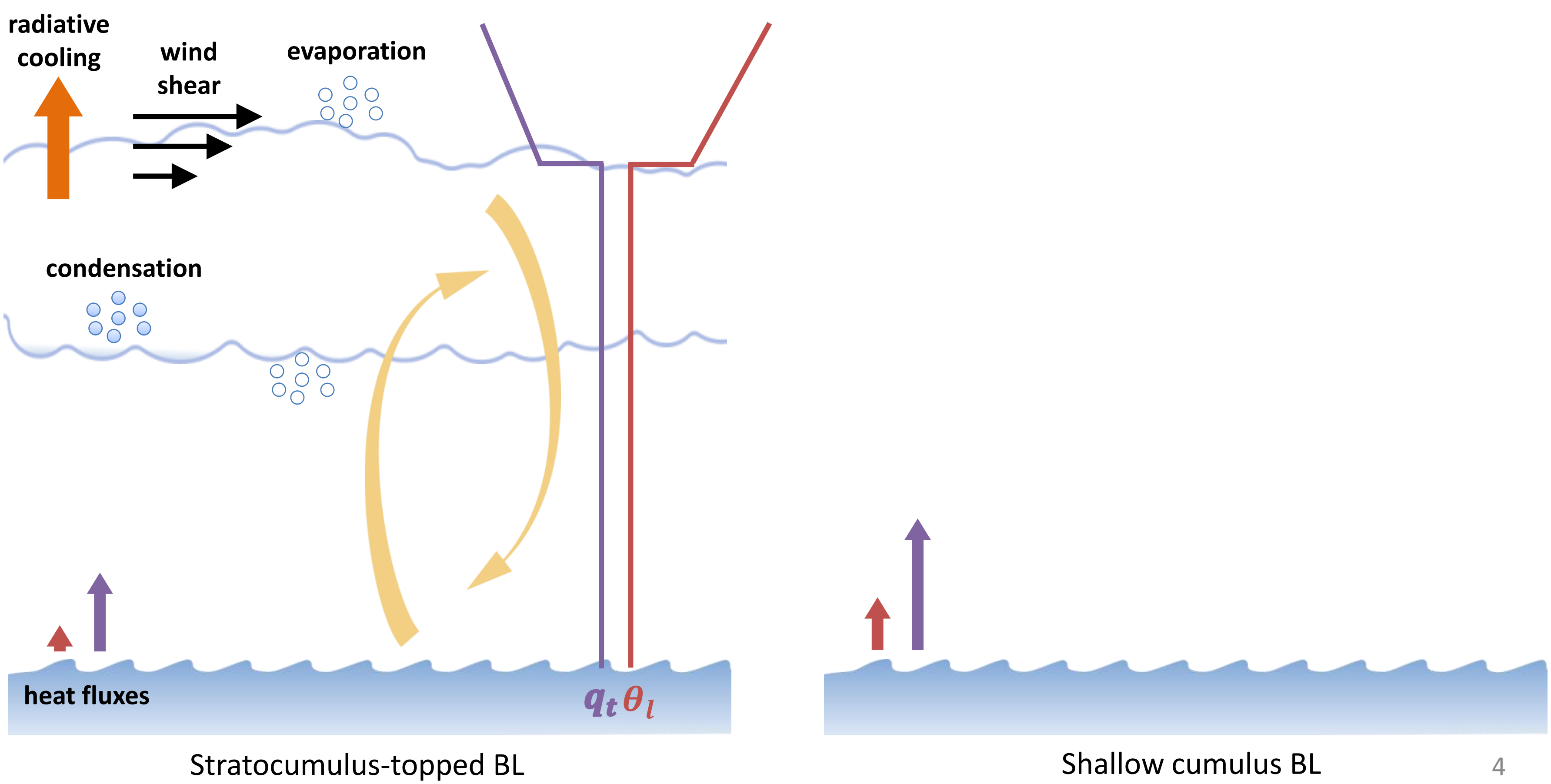
Subtropical regimes of atmospheric boundary layer



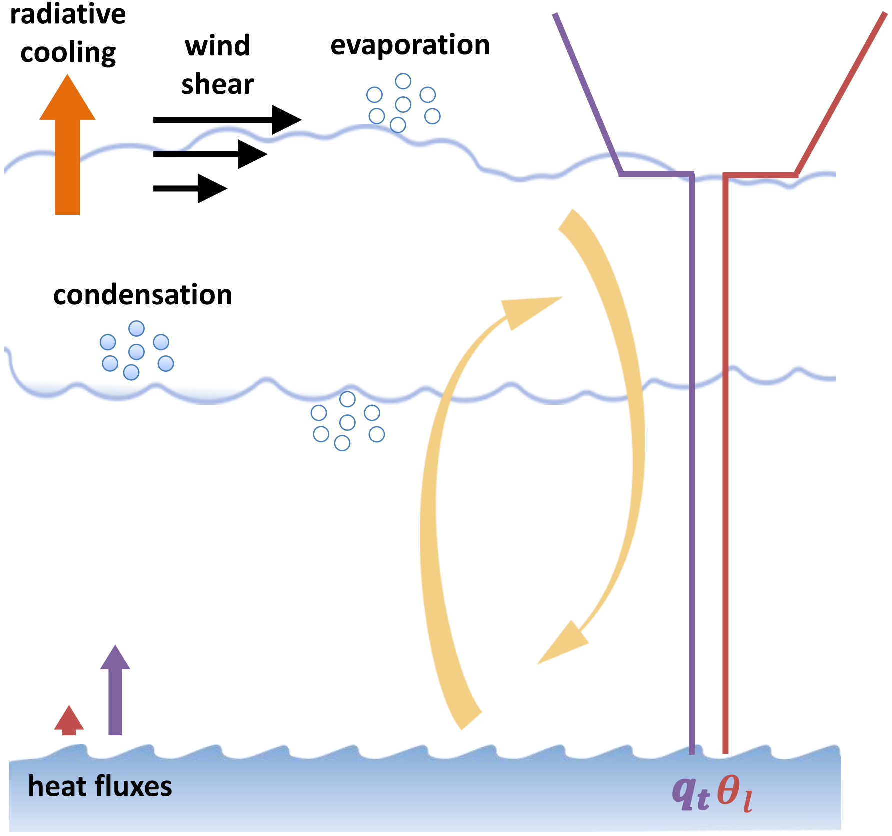
Stratocumulus-topped BL

Shallow cumulus BL

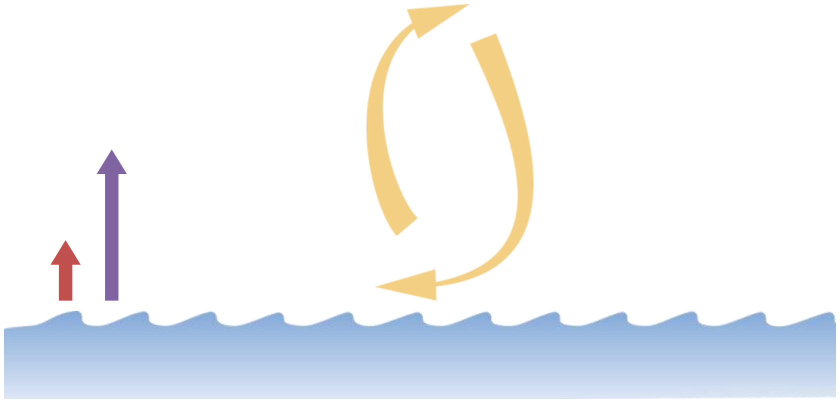
Subtropical regimes of atmospheric boundary layer



Subtropical regimes of atmospheric boundary layer

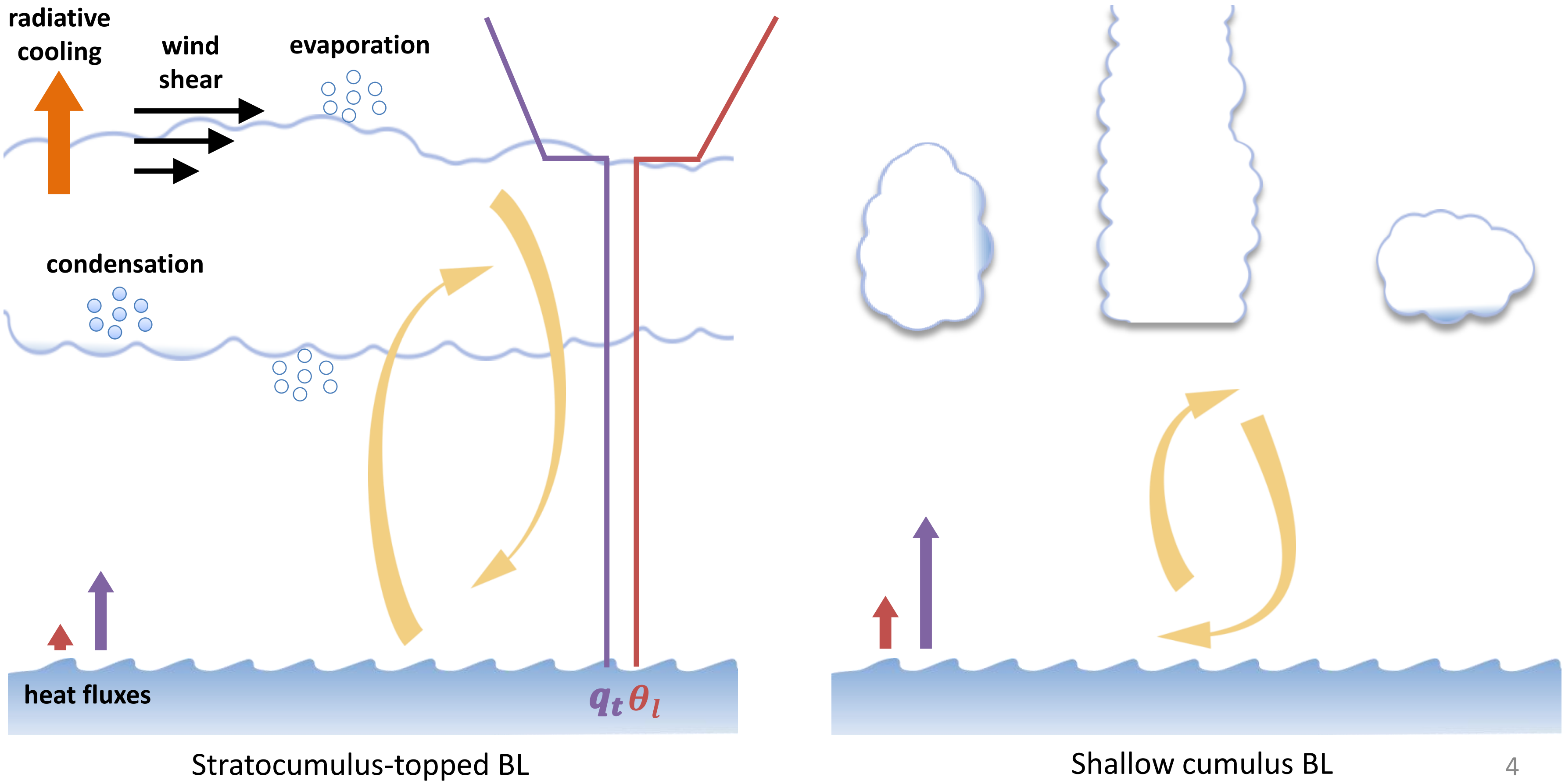


Stratocumulus-topped BL

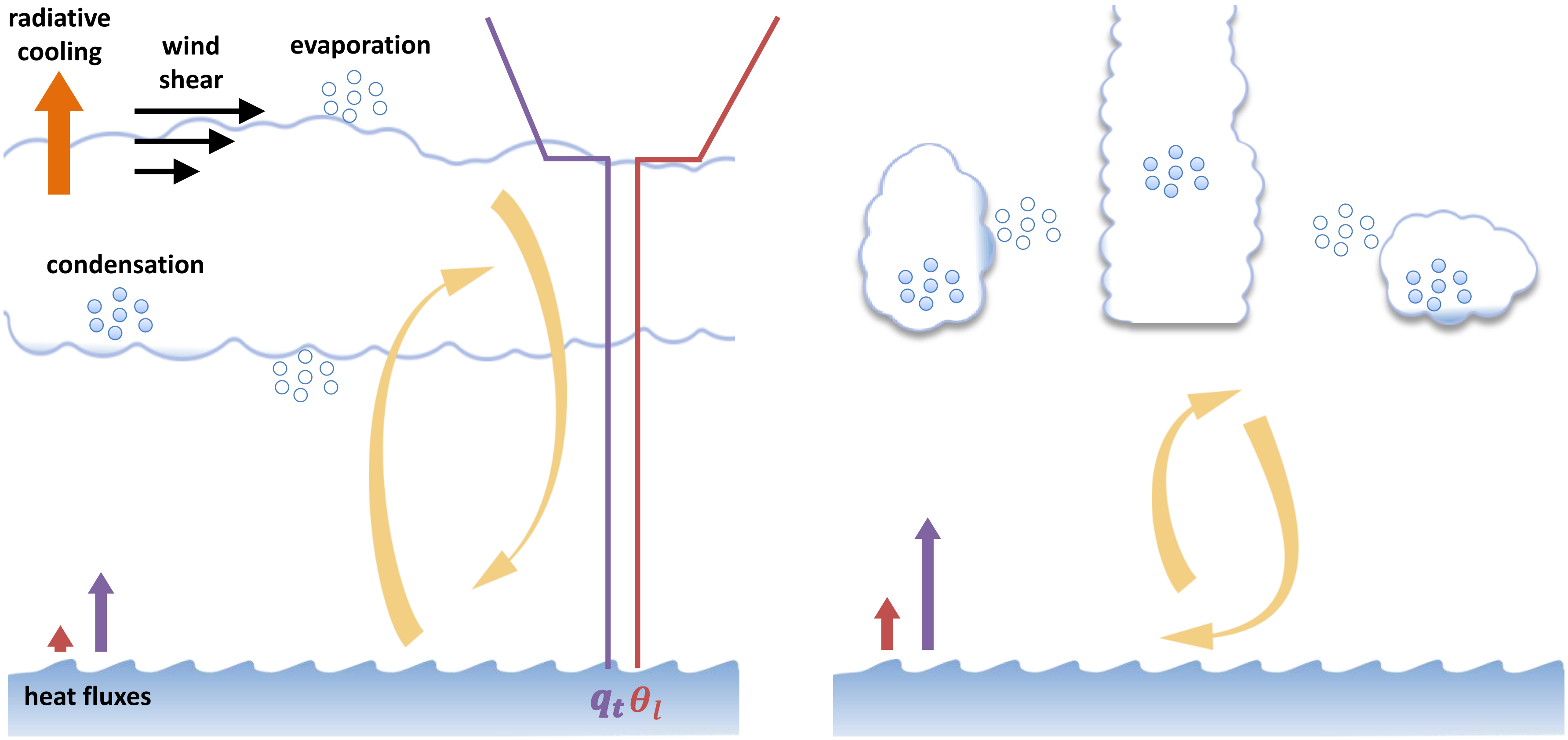


Shallow cumulus BL

Subtropical regimes of atmospheric boundary layer



Subtropical regimes of atmospheric boundary layer



Stratocumulus-topped BL

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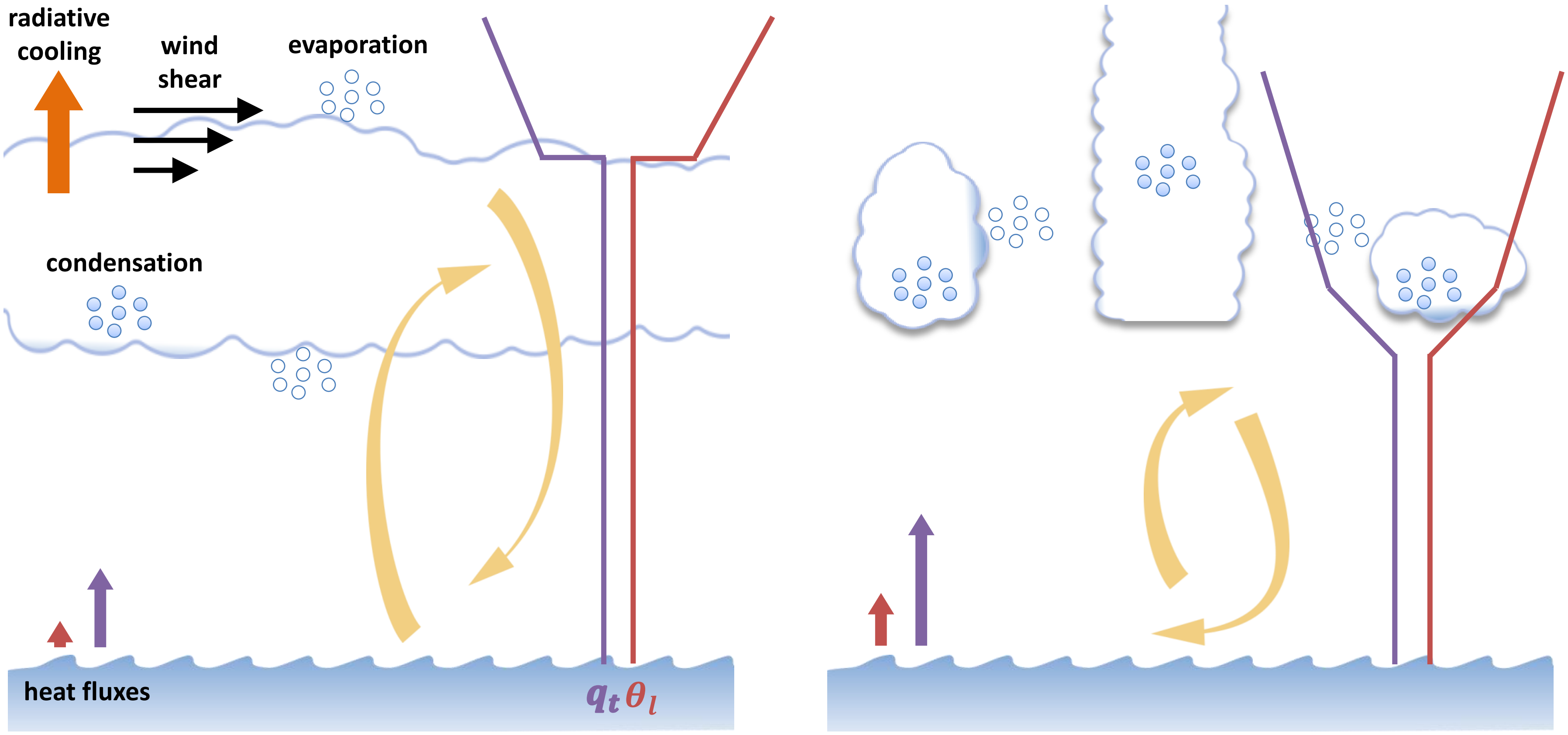
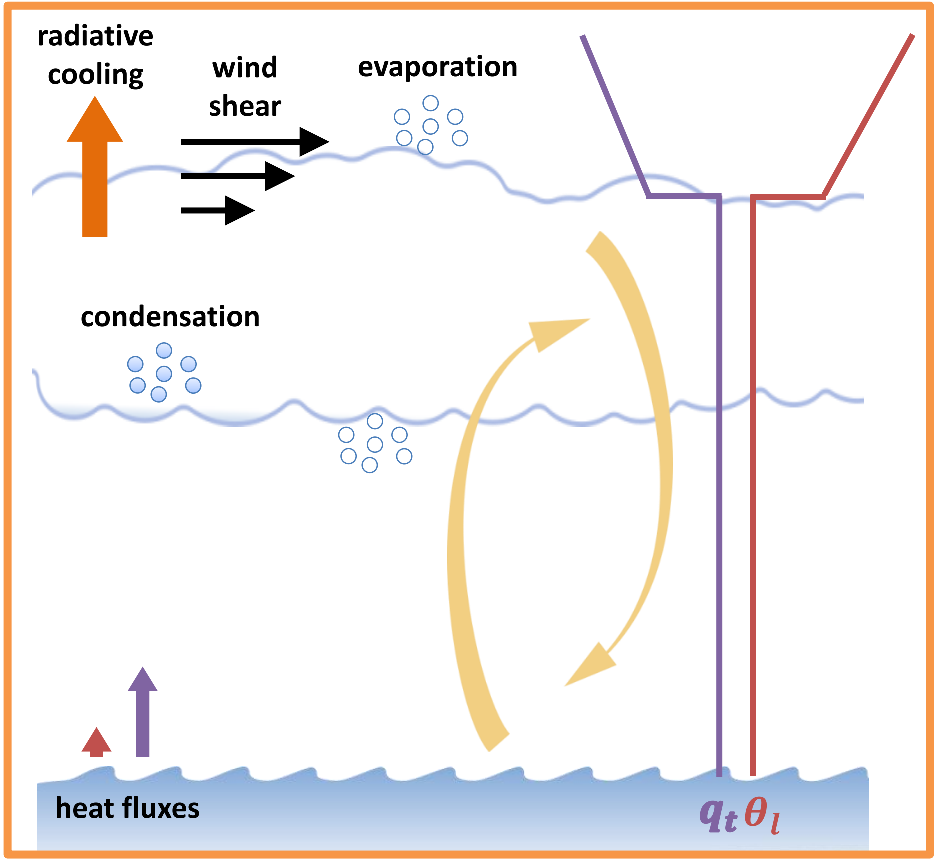
Subtropical regimes of atmospheric boundary layer



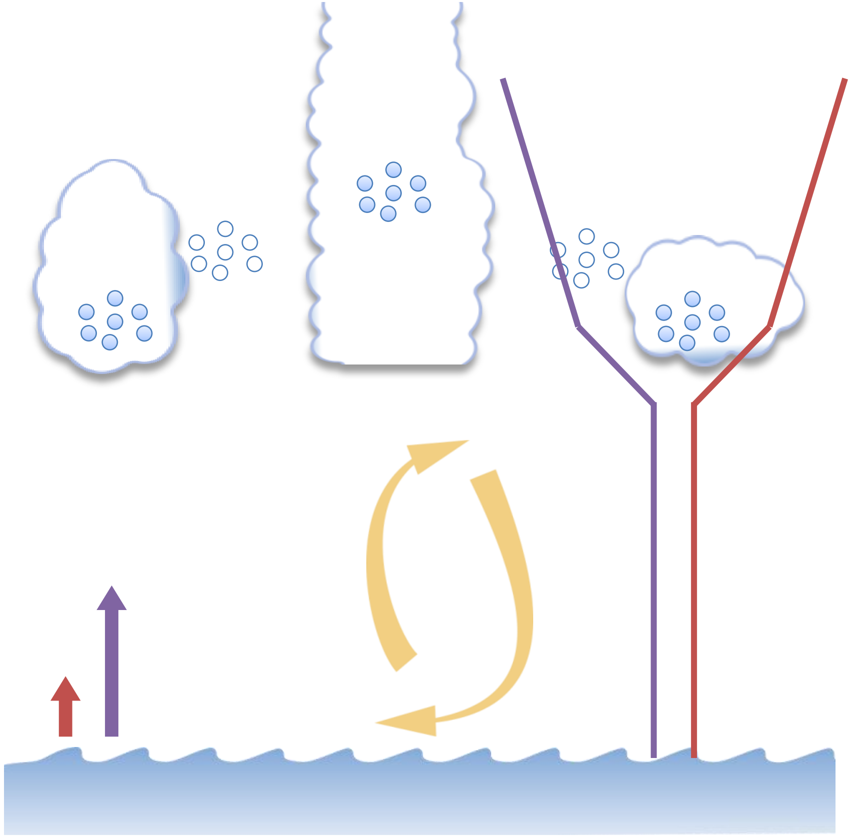
Stratocumulus-topped BL

Shallow cumulus BL

PART I: Stratocumulus-topped boundary layer

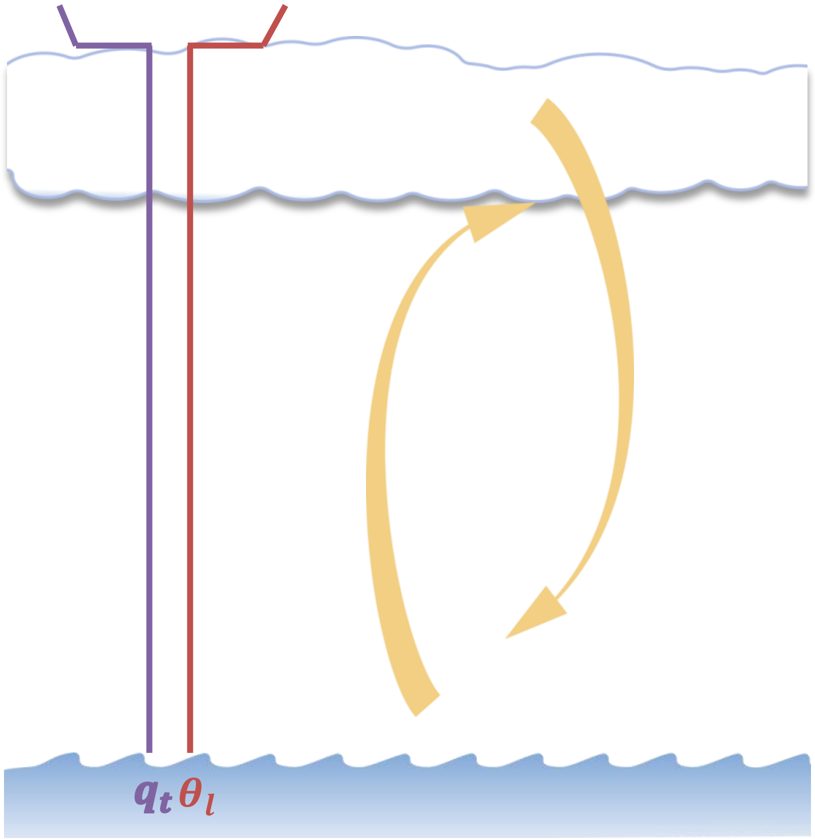


Stratocumulus-topped BL

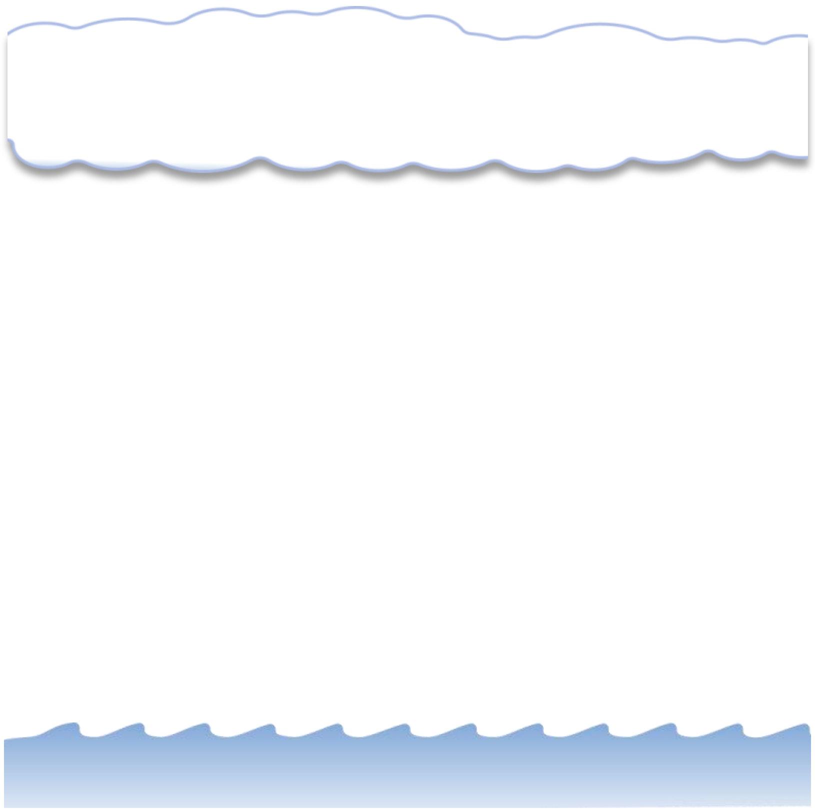


Shallow cumulus BL

Decoupling of stratocumulus-topped boundary layer

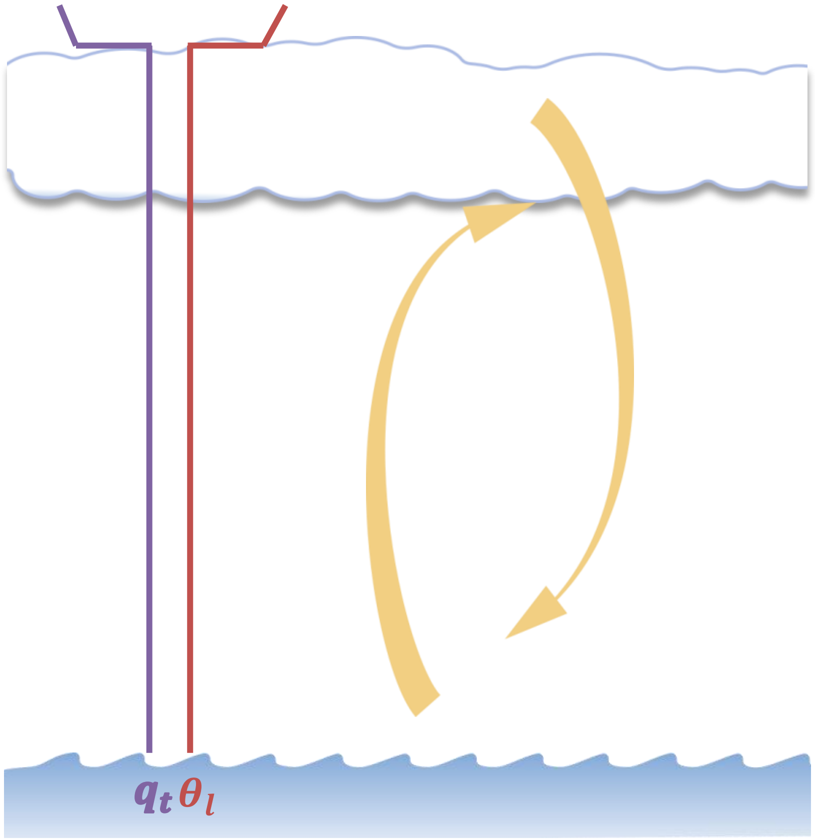


Coupled boundary layer

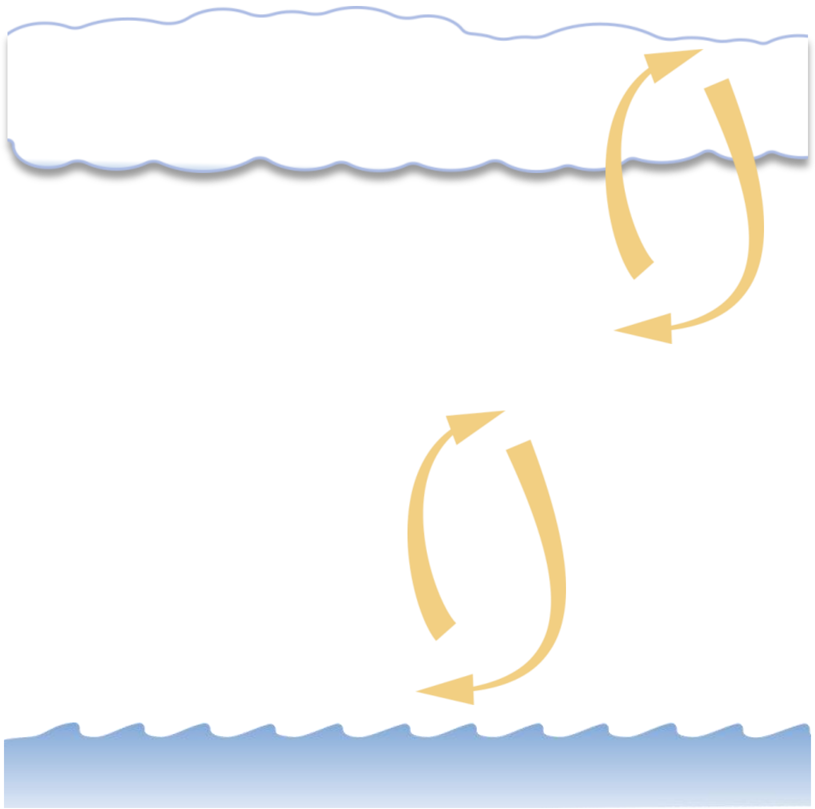


Decoupled boundary layer

Decoupling of stratocumulus-topped boundary layer

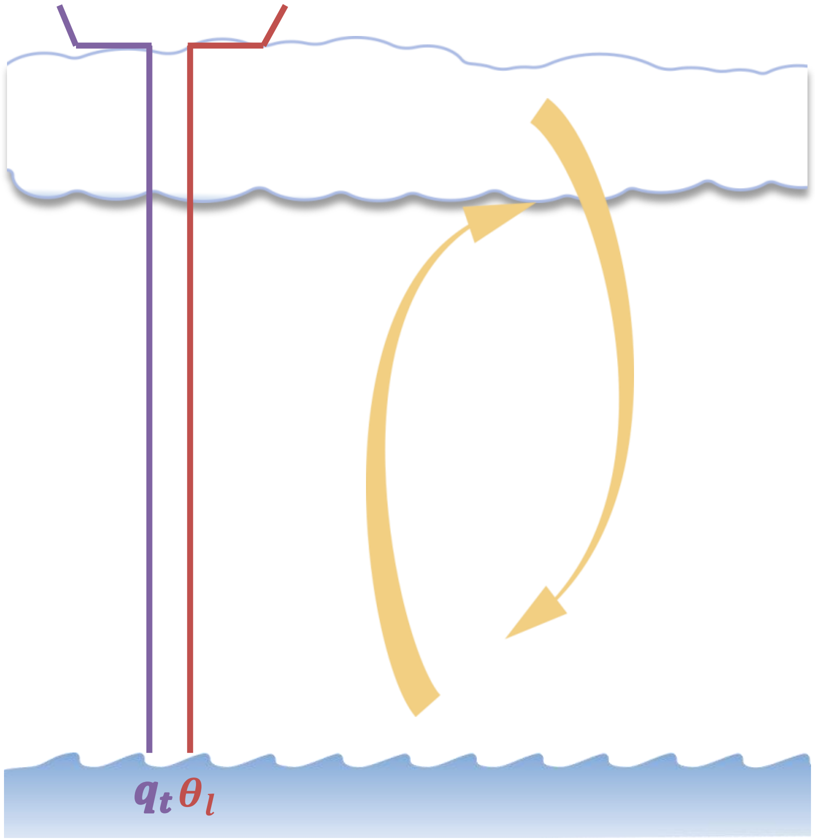


Coupled boundary layer

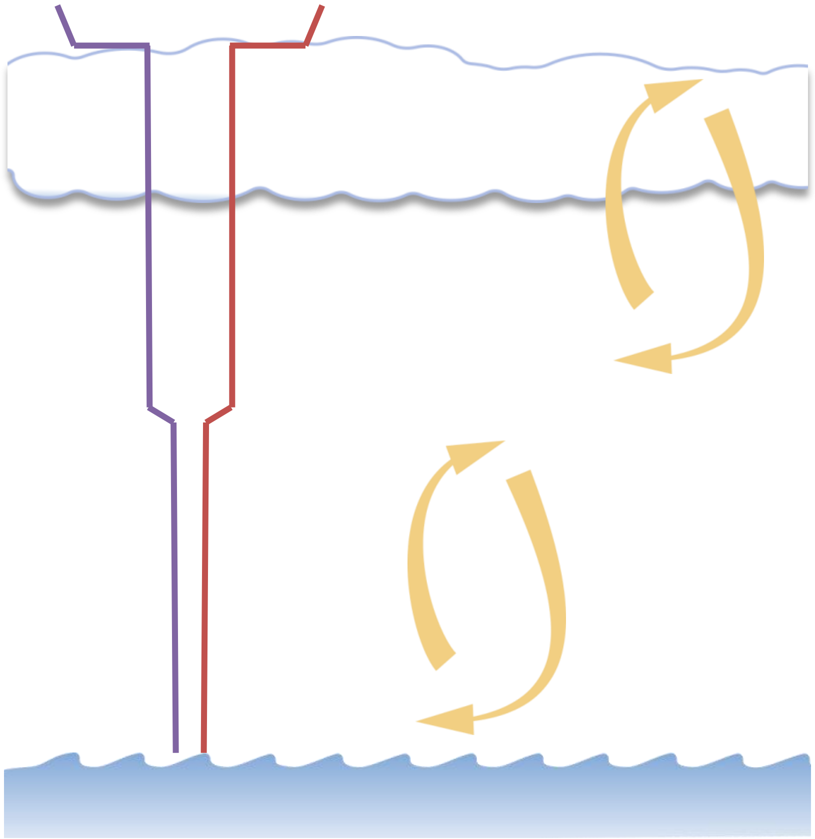


Decoupled boundary layer

Decoupling of stratocumulus-topped boundary layer

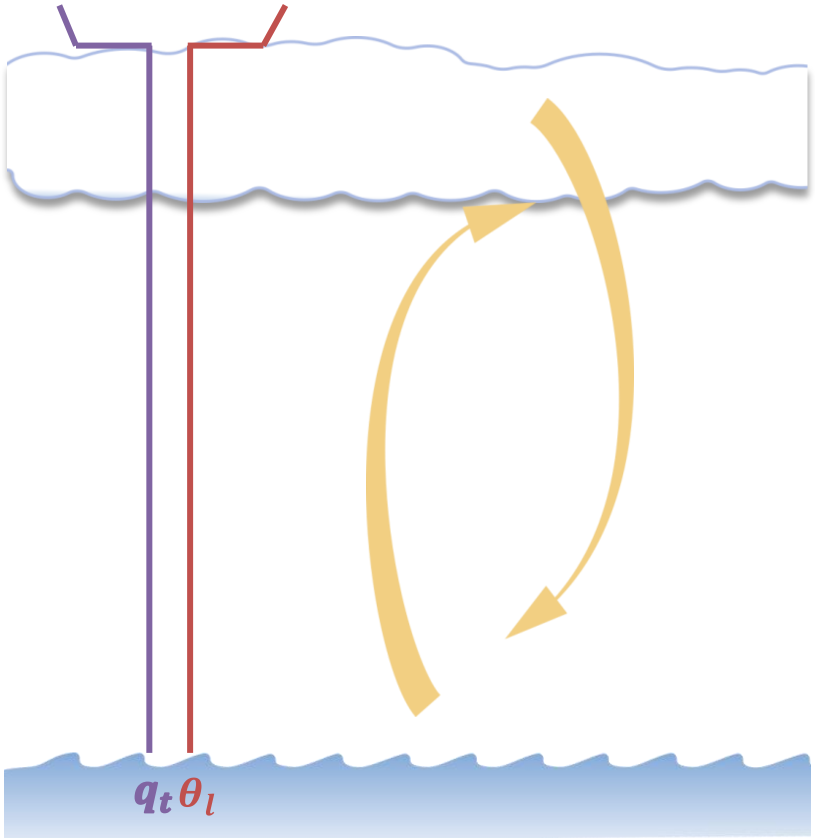


Coupled boundary layer

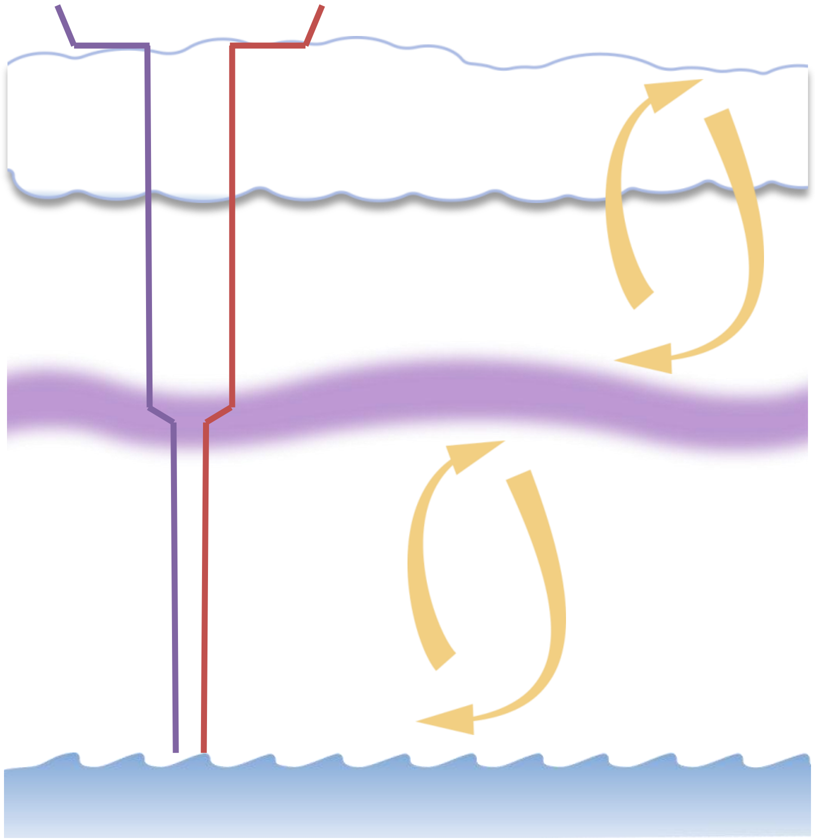


Decoupled boundary layer

Decoupling of stratocumulus-topped boundary layer

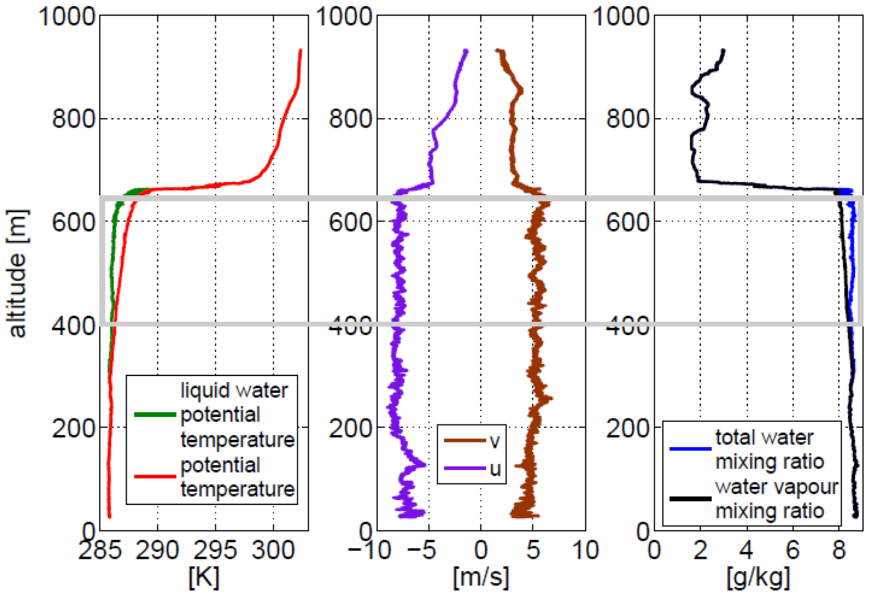


Coupled boundary layer



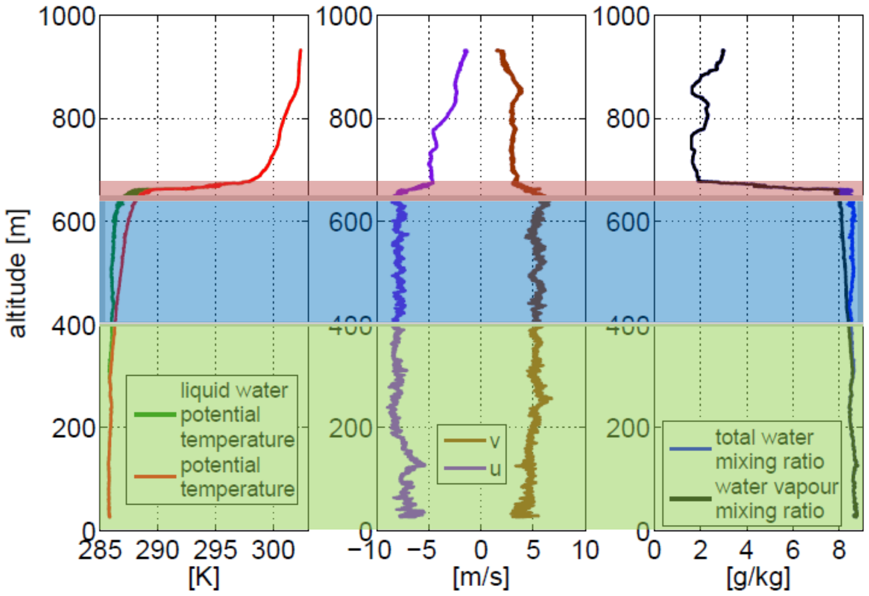
Decoupled boundary layer

Coupled/decoupled stratocumulus-topped boundary layer: examples



Malinowski et al. 2013: northeastern Pacific

Coupled/decoupled stratocumulus-topped boundary layer: examples



Free Tropospheric Layer (FTL)

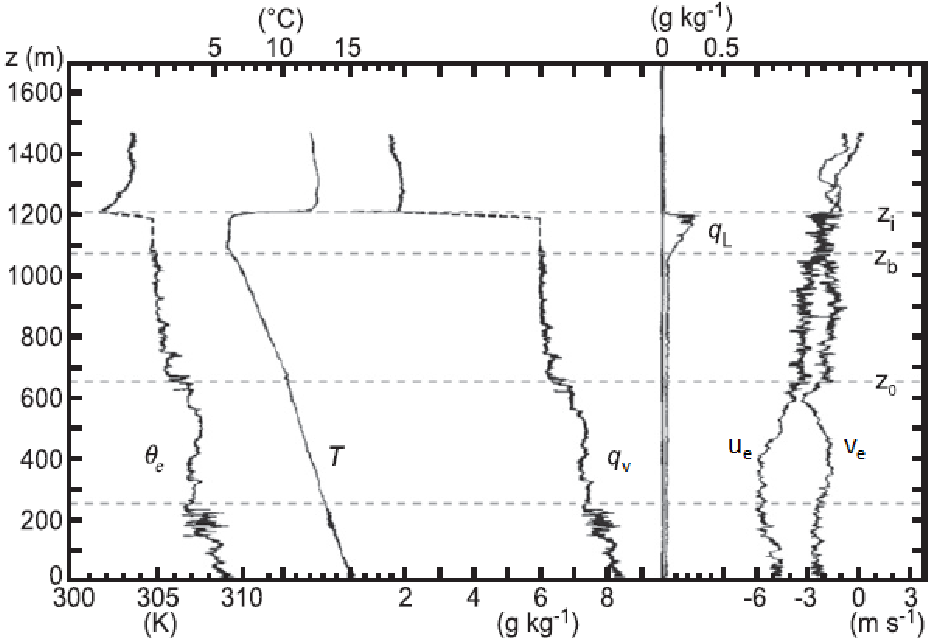
Entrainment Interface Layer (EIL)

Stratocumulus Layer (SCL)

Subcloud Layer (SBL)

Malinowski et al. 2013: northeastern Pacific

Coupled/decoupled stratocumulus-topped boundary layer: examples



Nicholls and Leighton 1986: North Sea

Coupled/decoupled stratocumulus-topped boundary layer: examples

Free Tropospheric Layer (FTL)

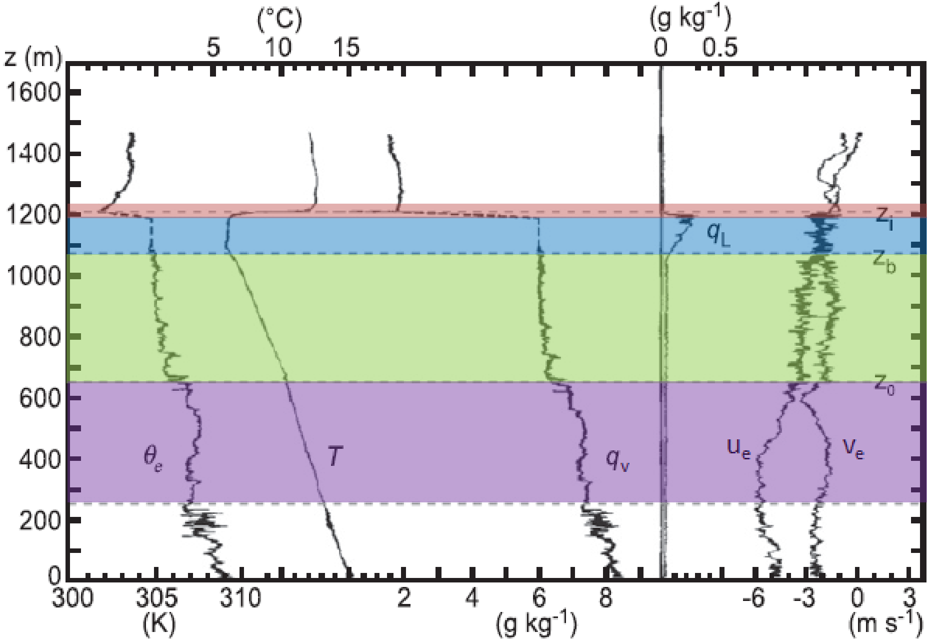
Entrainment Interface Layer (EIL)

Stratocumulus Layer (SCL)

Subcloud Layer (SBL)

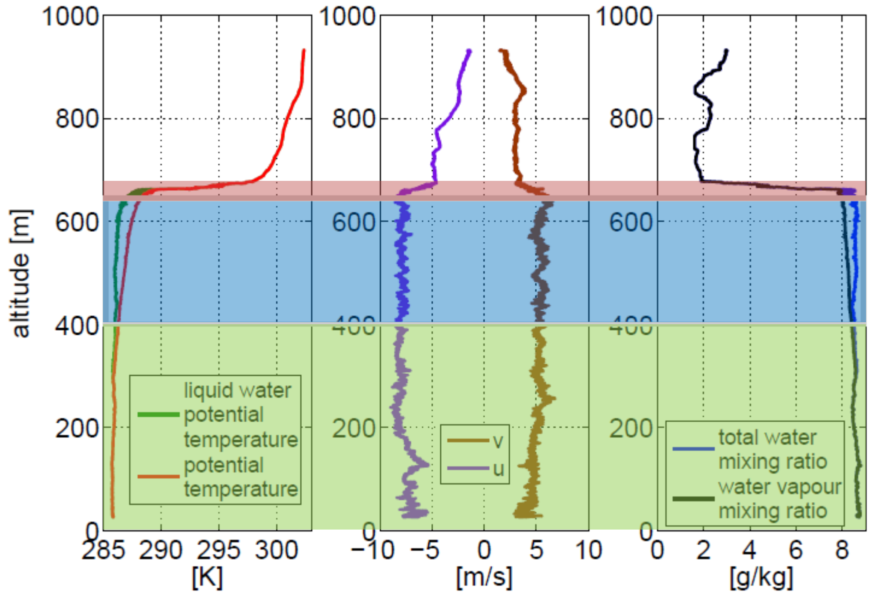
Transition Layer (TSL)

Surface Mixed Layer (SML)

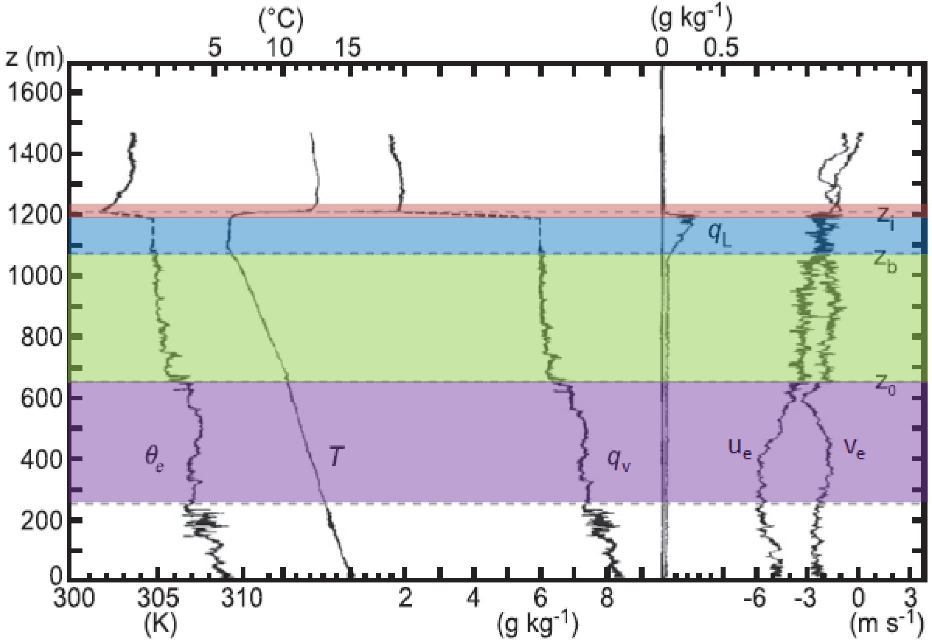


Nicholls and Leighton 1986: North Sea

Coupled/decoupled stratocumulus-topped boundary layer: examples

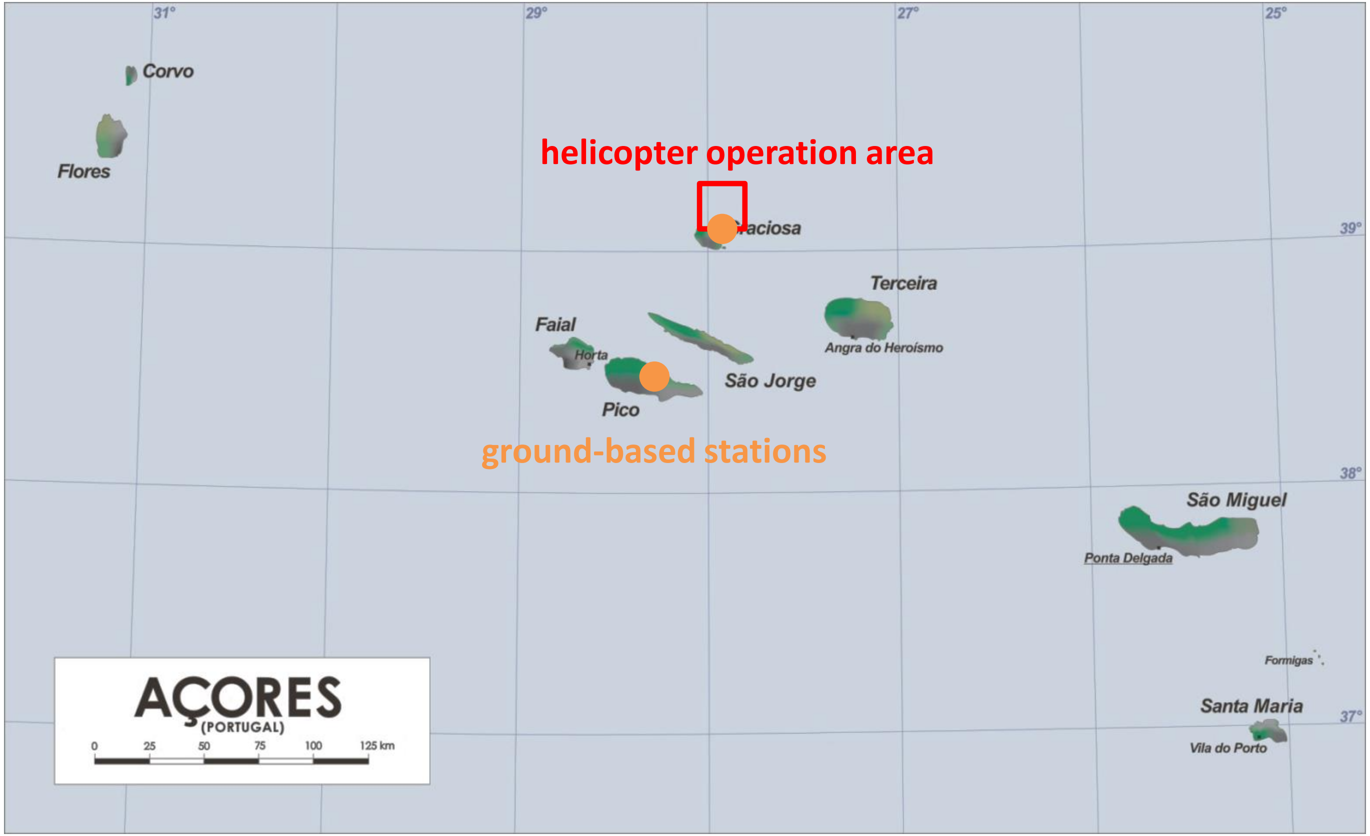


Malinowski et al. 2013: northeastern Pacific



Nicholls and Leighton 1986: North Sea

Field campaign ACORES 2017



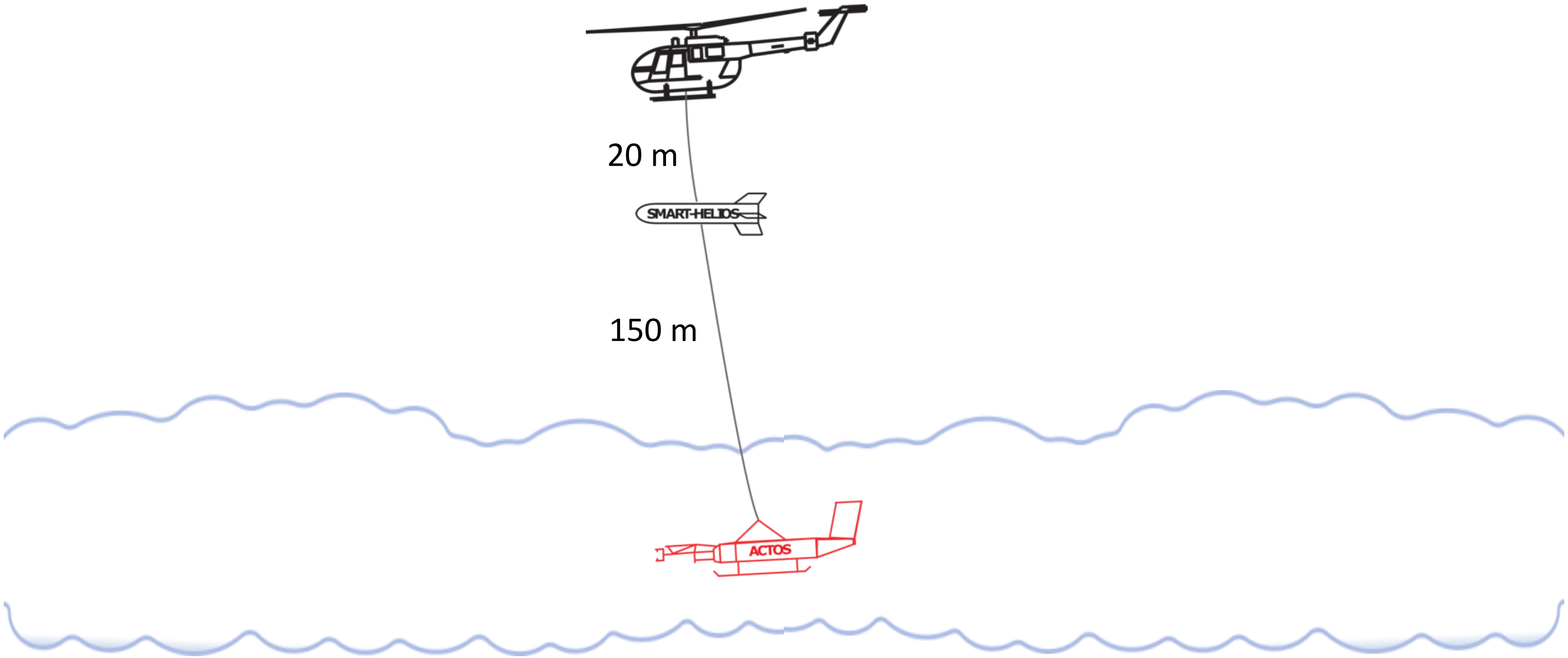
Azores stratoCumulus measurements Of Radiation, turbulEnce and aeroSols

2-22 July 2017

Helicopter sampling:
17 flights x 2 hours

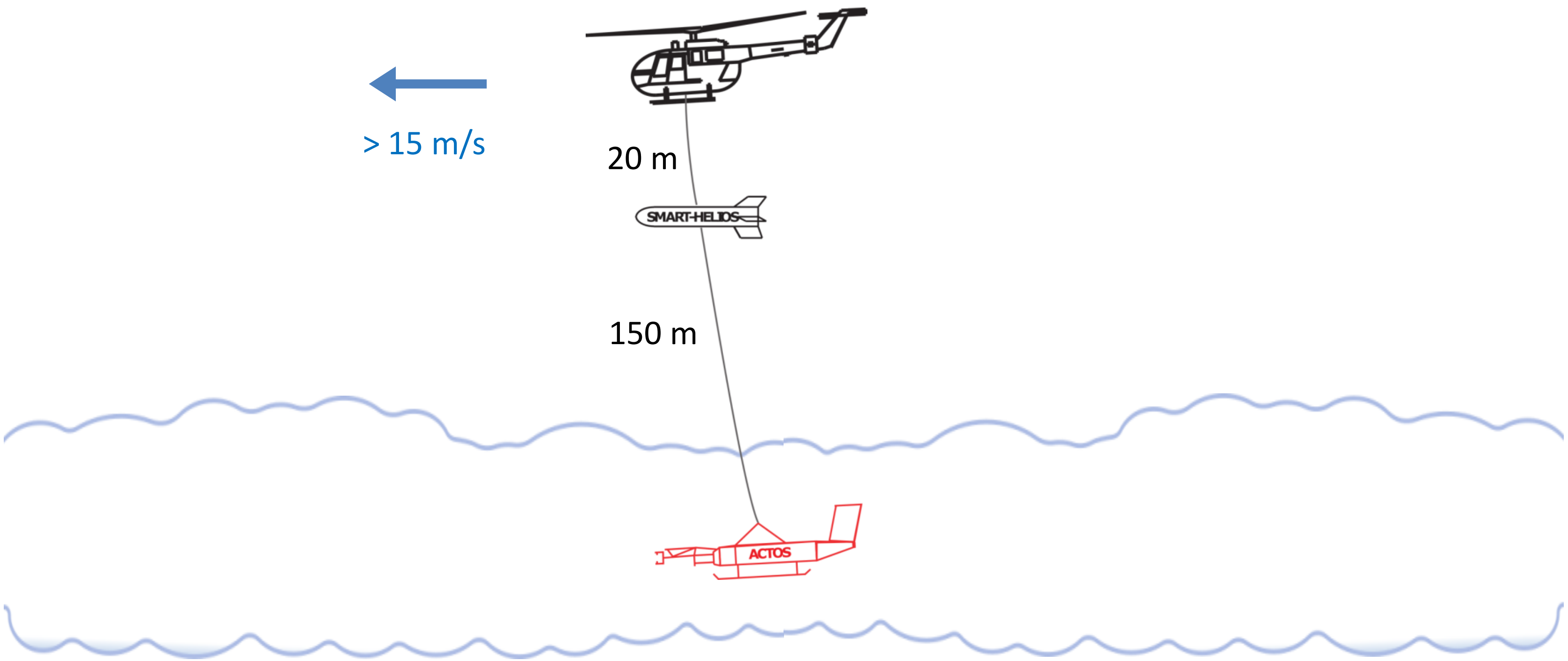
Siebert et al. 2021

ACORES: sampling strategy



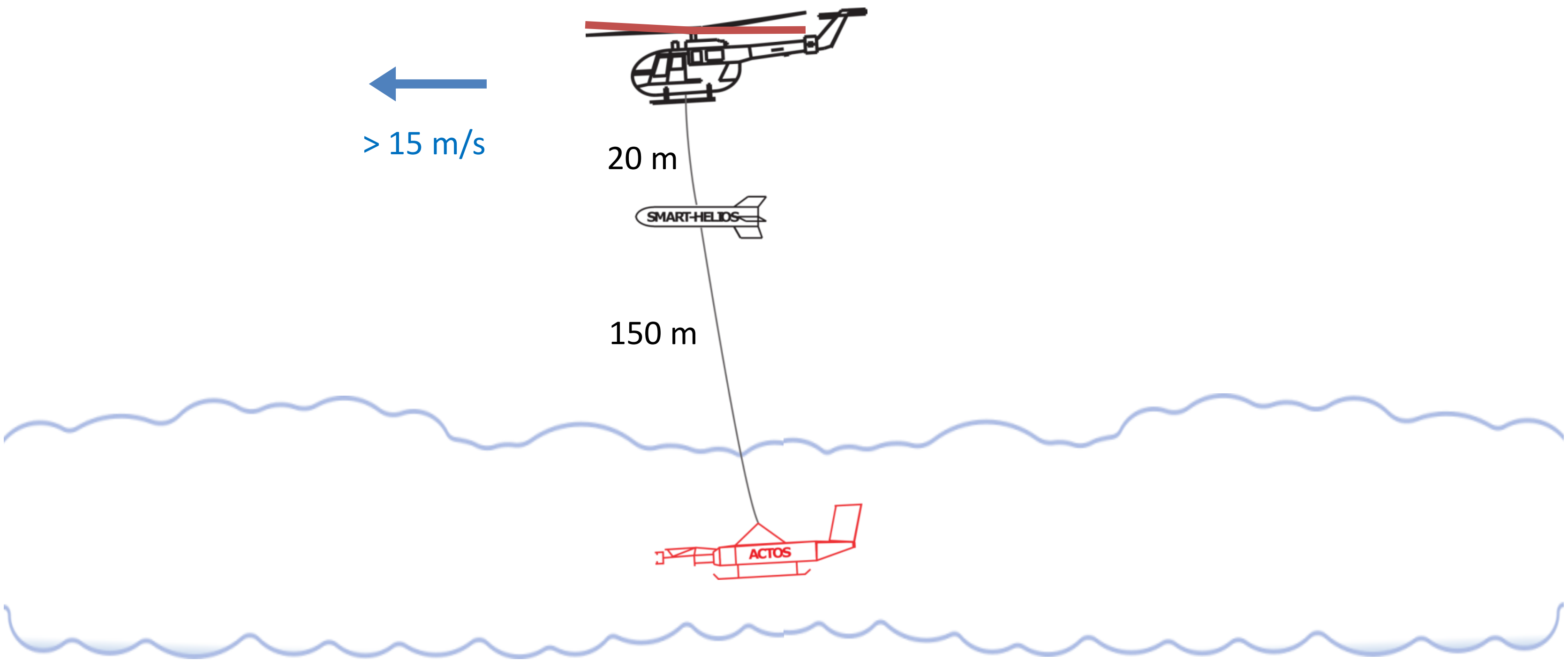
See also: Siebert et al. 2006

ACORES: sampling strategy



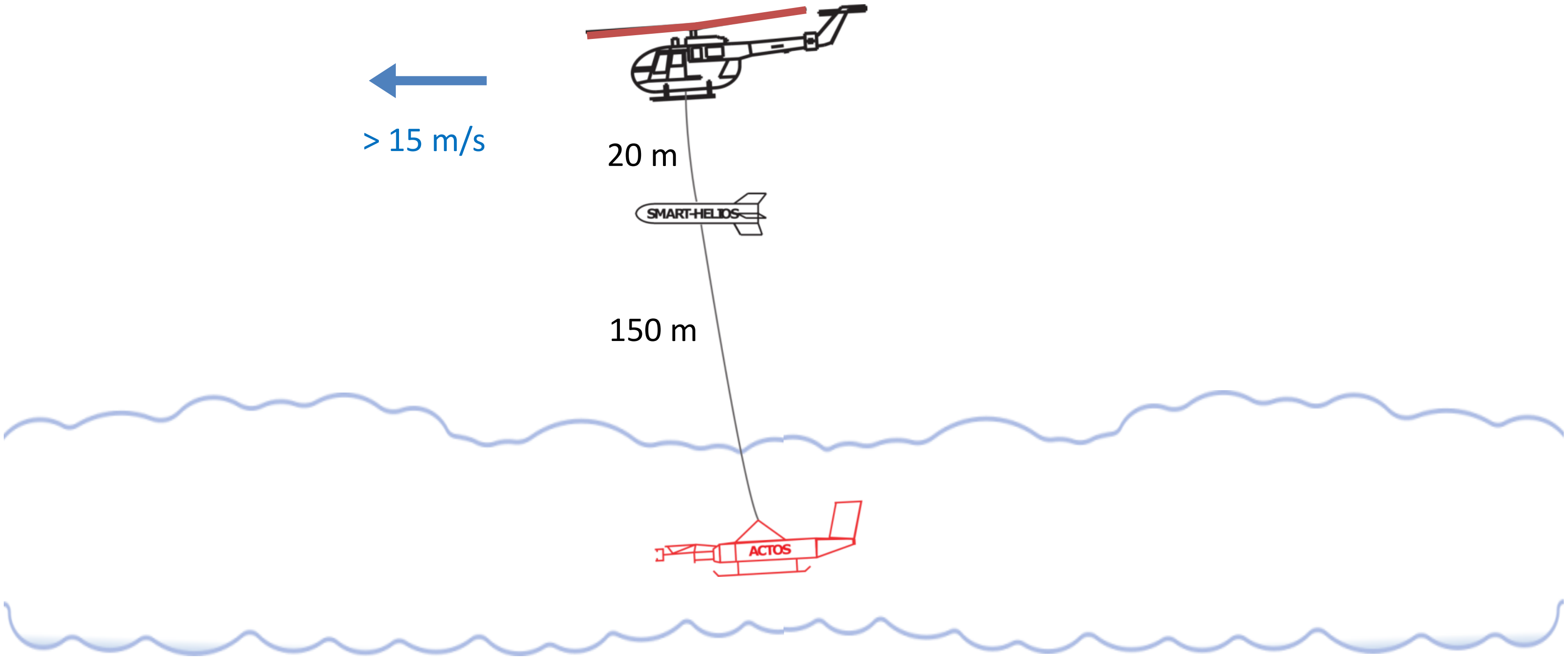
See also: Siebert et al. 2006

ACORES: sampling strategy



See also: Siebert et al. 2006

ACORES: sampling strategy



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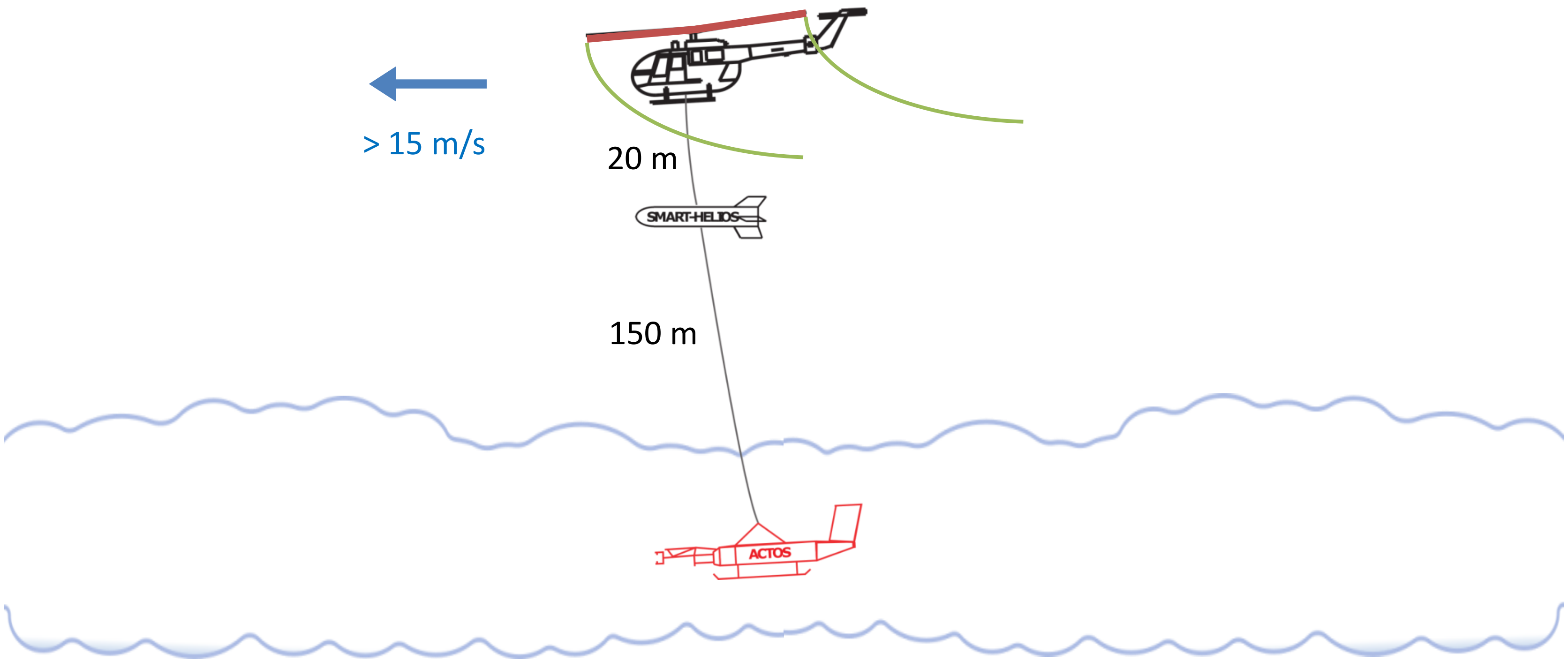
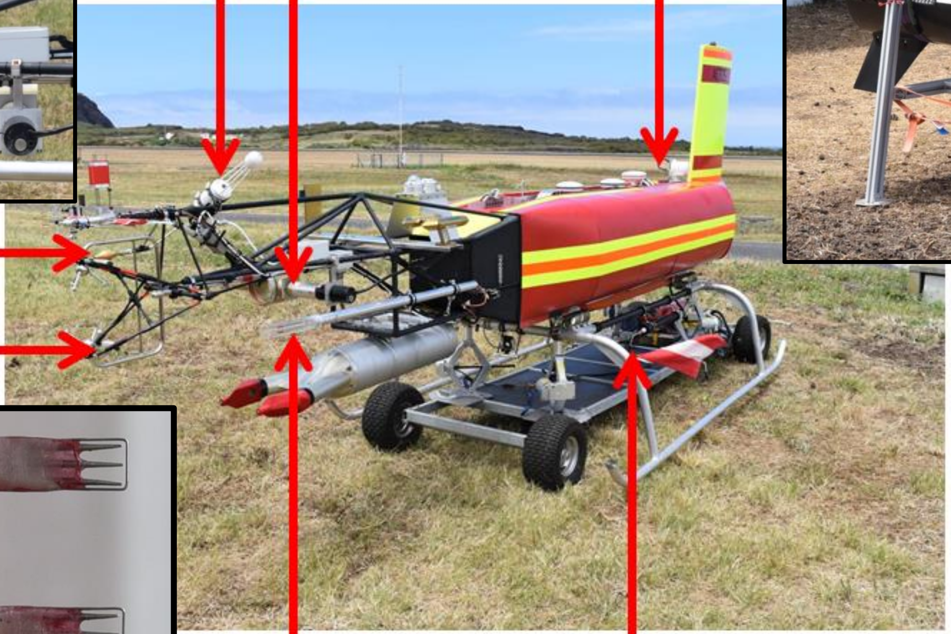
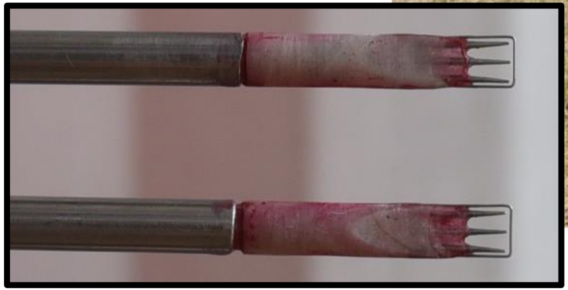
ACORES: sampling strategy



See also: Siebert et al. 2006

ACORES: Instrumentation



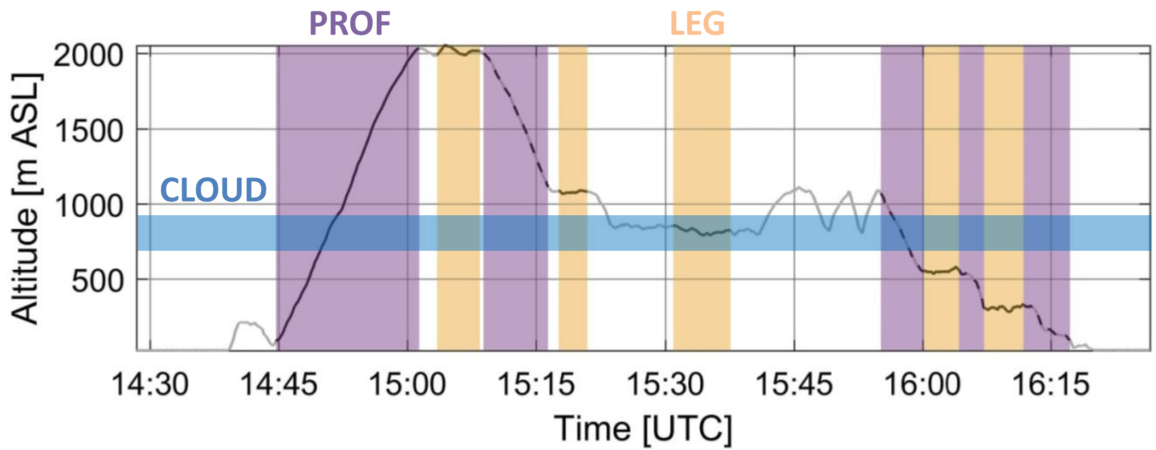


ACORES: Selected instruments

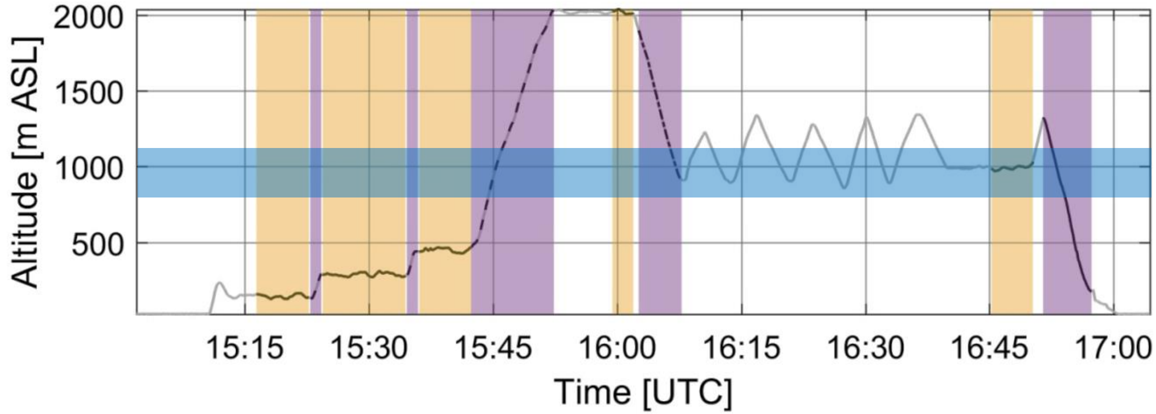
Variable		Instrument	Samp.	Resolution	References
U, dd	horizontal wind speed and direction	ultrasonic anemometer-thermometer Solent HS, Gill Instruments + inertial navigation + GPS	100 Hz	~ 20 cm	Siebert and Teichmann 2000
u, w	longitudinal and vertical wind components				Nowak et al. 2021
T_v	virtual temperature				Siebert and Muschinski 2001
T	temperature	UltraFast Thermometer, University of Warsaw	4 kHz	~ 0.5 cm	Haman et al. 1997 Nowak et al. 2018
q_v	specific humidity	open-path LI-7500, LI-COR Environmental	20 Hz	~ 1 m	Lampert et al. 2018
q_l	liquid water mass fraction	Particle Volume Meter, Gerber Scientific	1 kHz	~ 2 cm	Gerber et al. 1994 Wendisch et al. 2002

See also: Siebert et al. 2006, Siebert et al. 2021

ACORES: Flight patterns

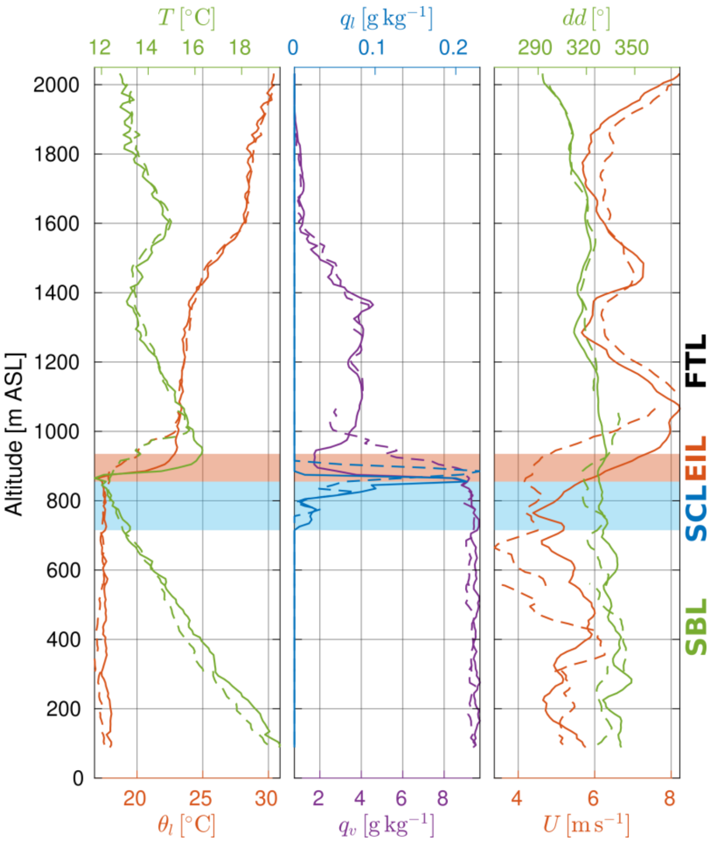


Flight #5, 8 July 2017
Coupled boundary layer



Flight #14, 18 July 2017
Decoupled boundary layer

Stratocumulus-topped BL: Stratification



Free Tropospheric Layer

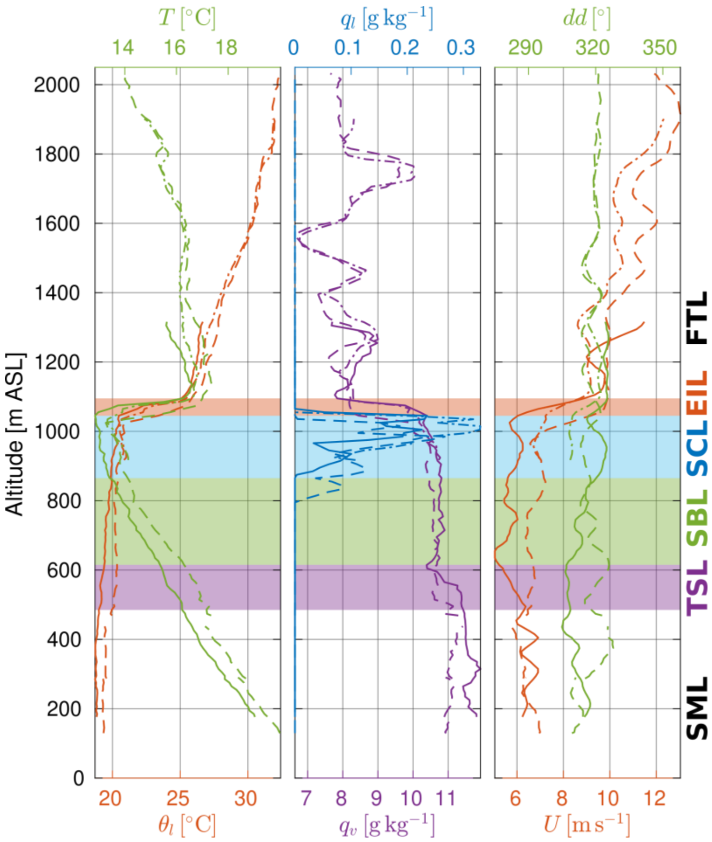
Entrainment Interface Layer

Stratocumulus Layer

Subcloud Layer

Transition Layer

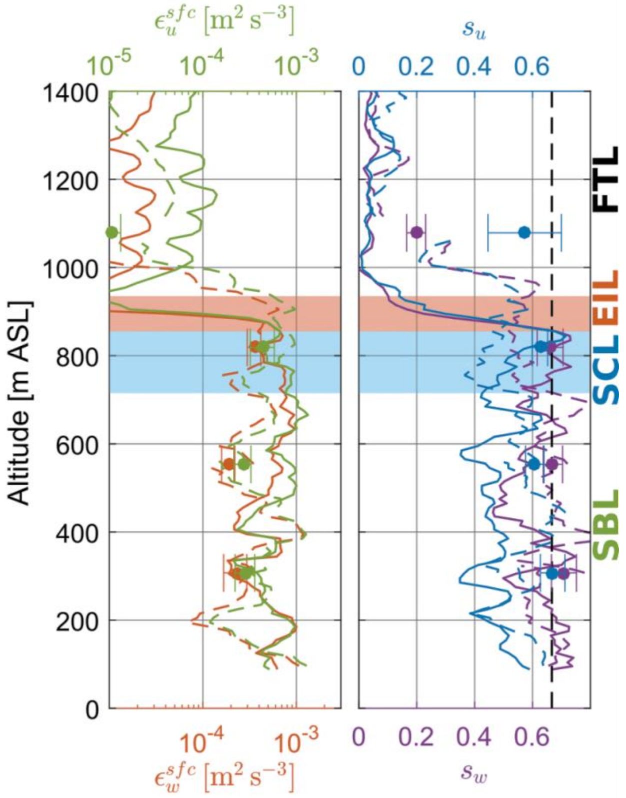
Surface Mixed Layer



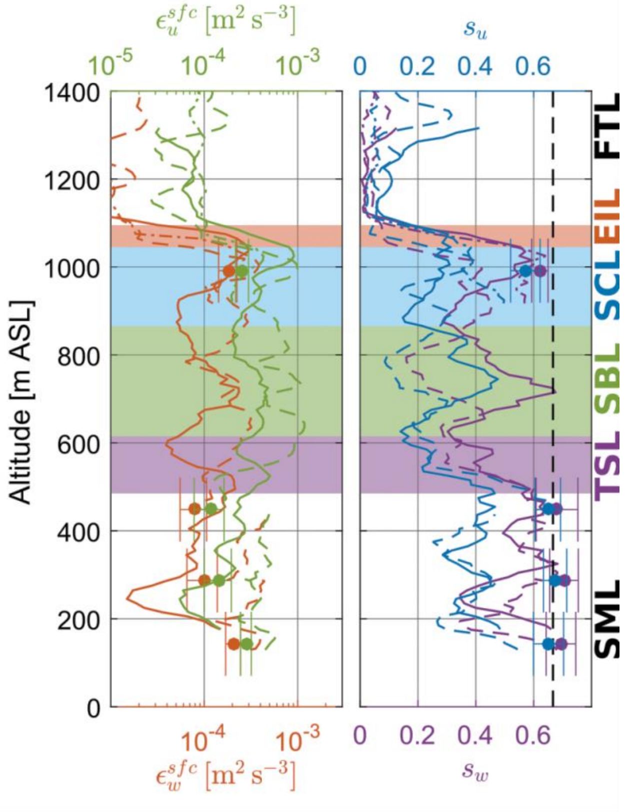
Coupled boundary layer

Decoupled boundary layer

Stratocumulus-topped BL: Epsilon and structure function scaling (1)

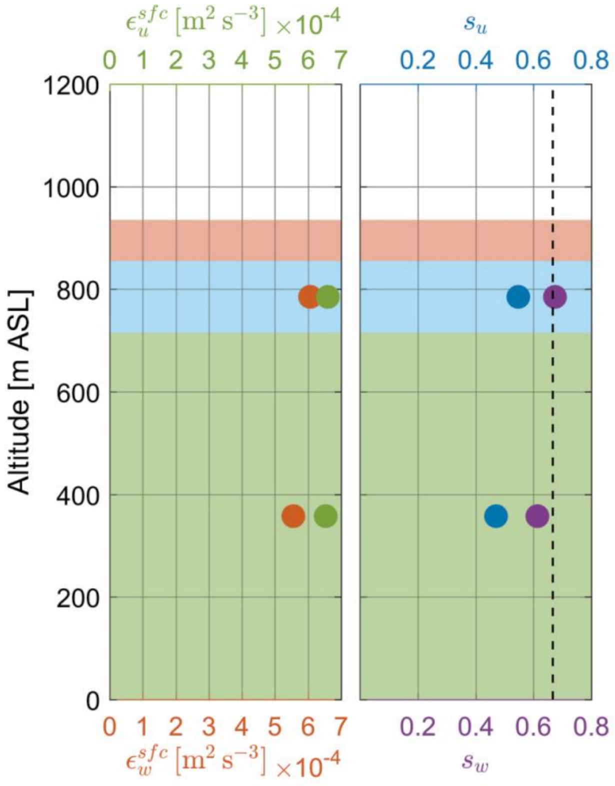


Coupled boundary layer

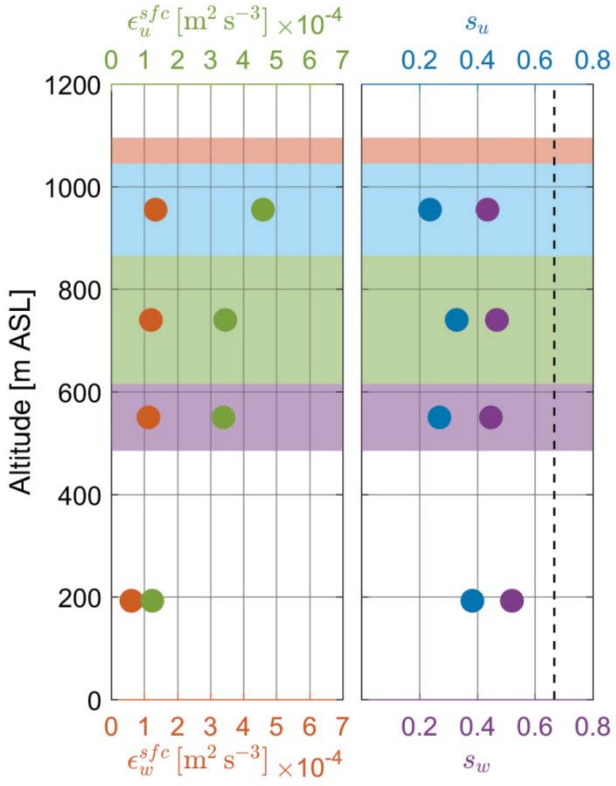


Decoupled boundary layer

Stratocumulus-topped BL: Epsilon and structure function scaling (2)

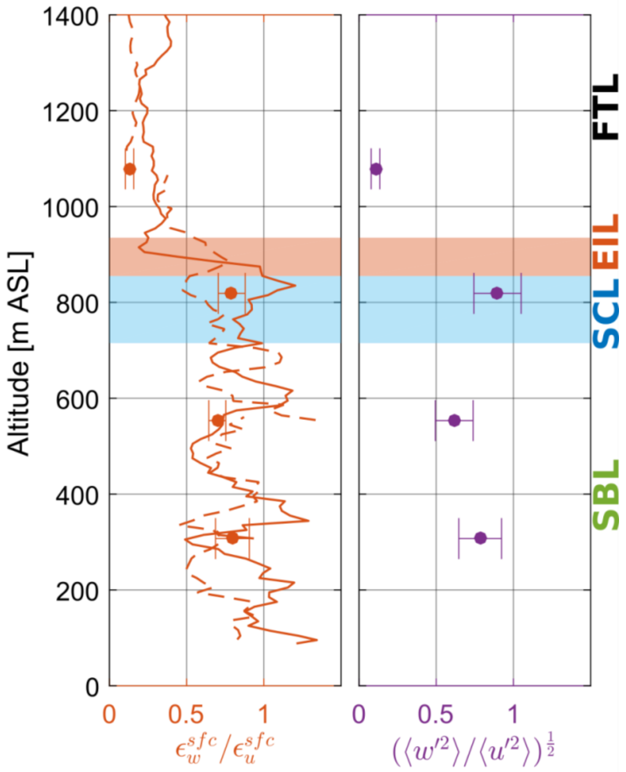


Coupled boundary layer

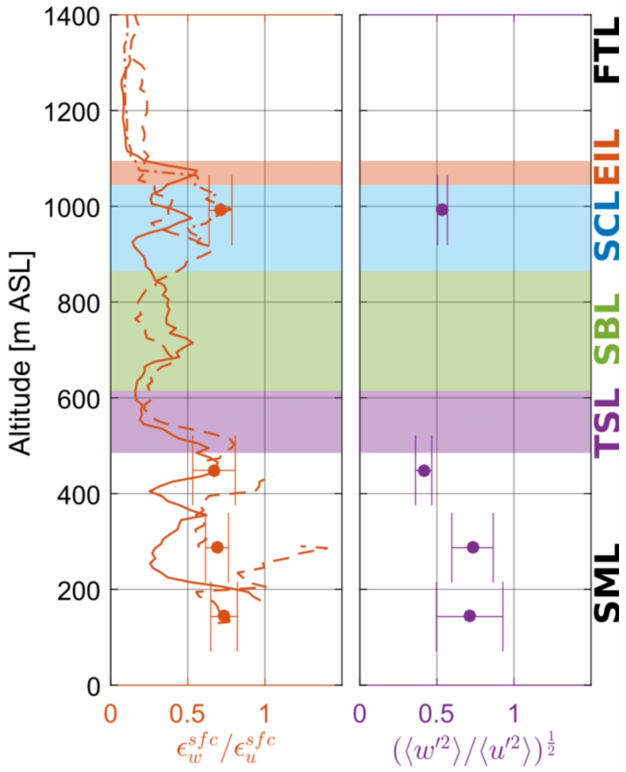


Decoupled boundary layer

Stratocumulus-topped BL: Anisotropy

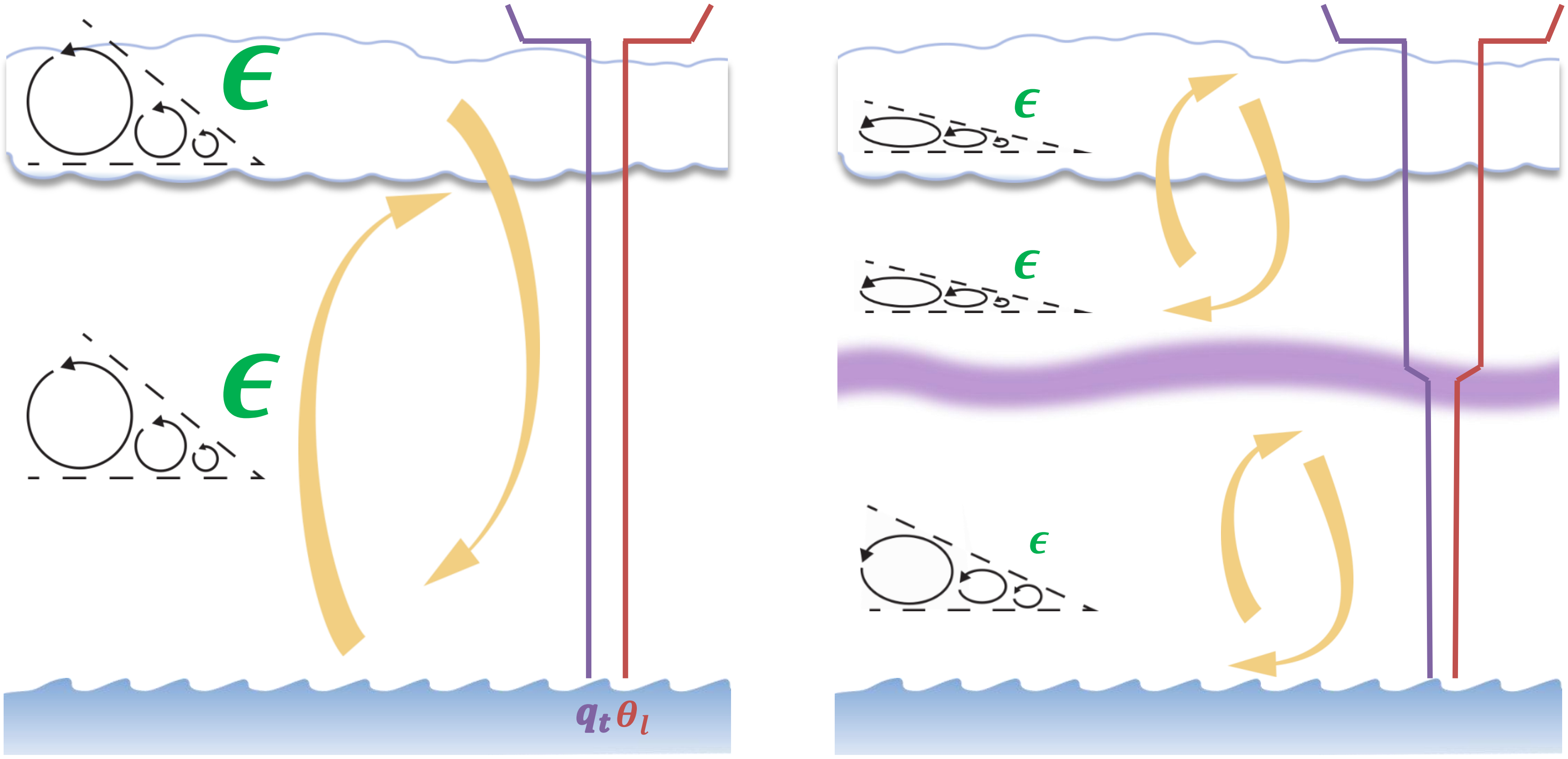


Coupled boundary layer



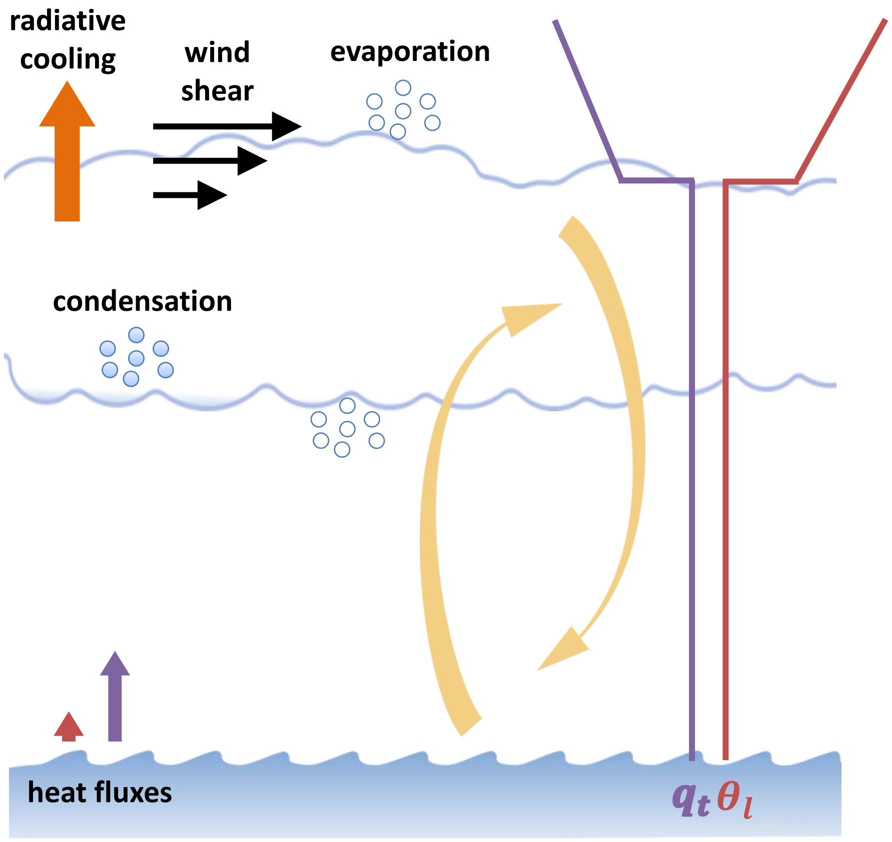
Decoupled boundary layer

Stratocumulus-topped BL: Summary

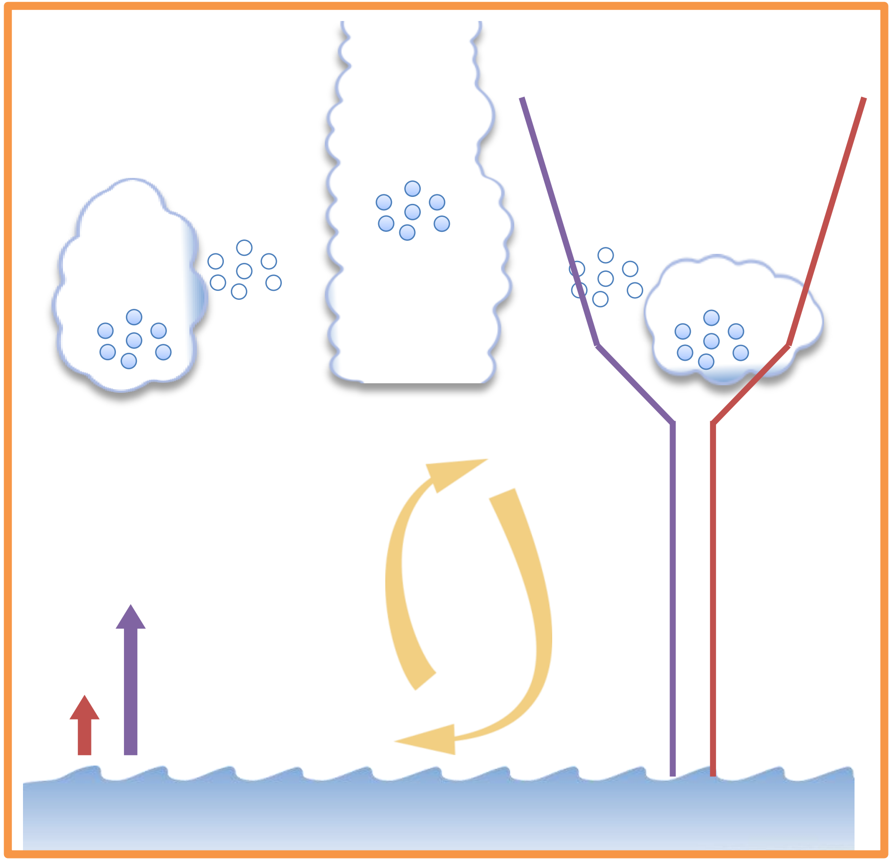


Coupled See also Nowak et al. 2021 Decoupled

PART II: Shallow-cumulus boundary layer

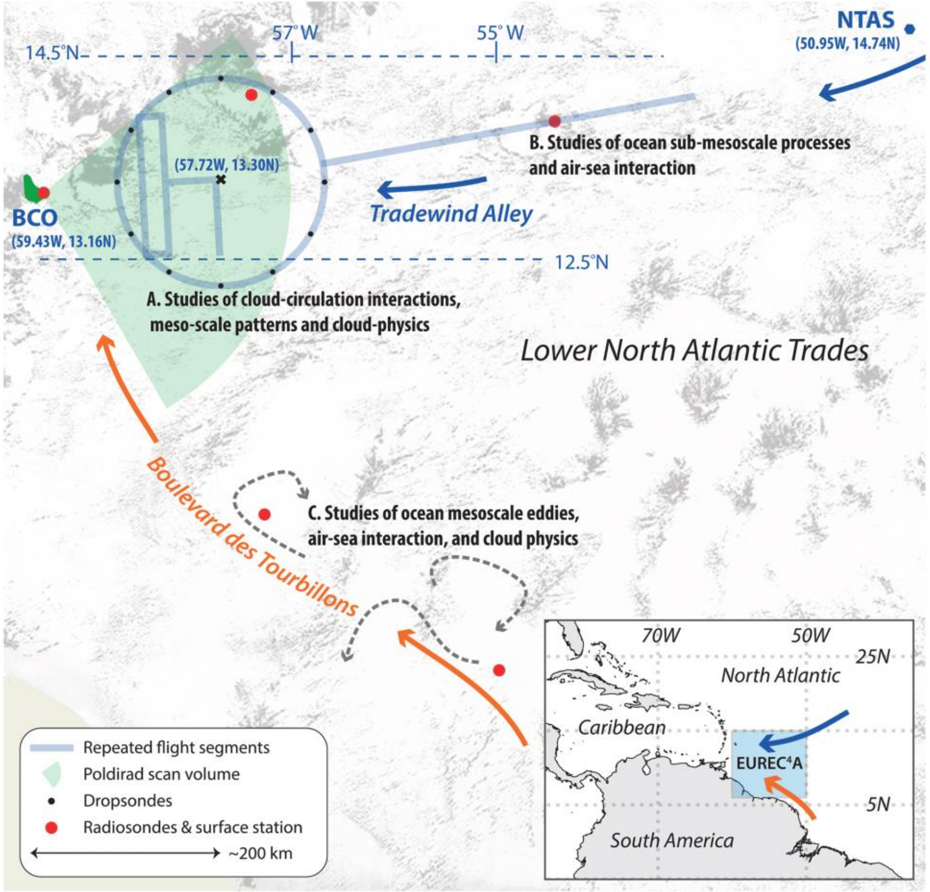


Stratocumulus-topped BL



Shallow cumulus BL

Field campaign EUREC4A 2020



Elucidating the role of clouds–circulation coupling in climate

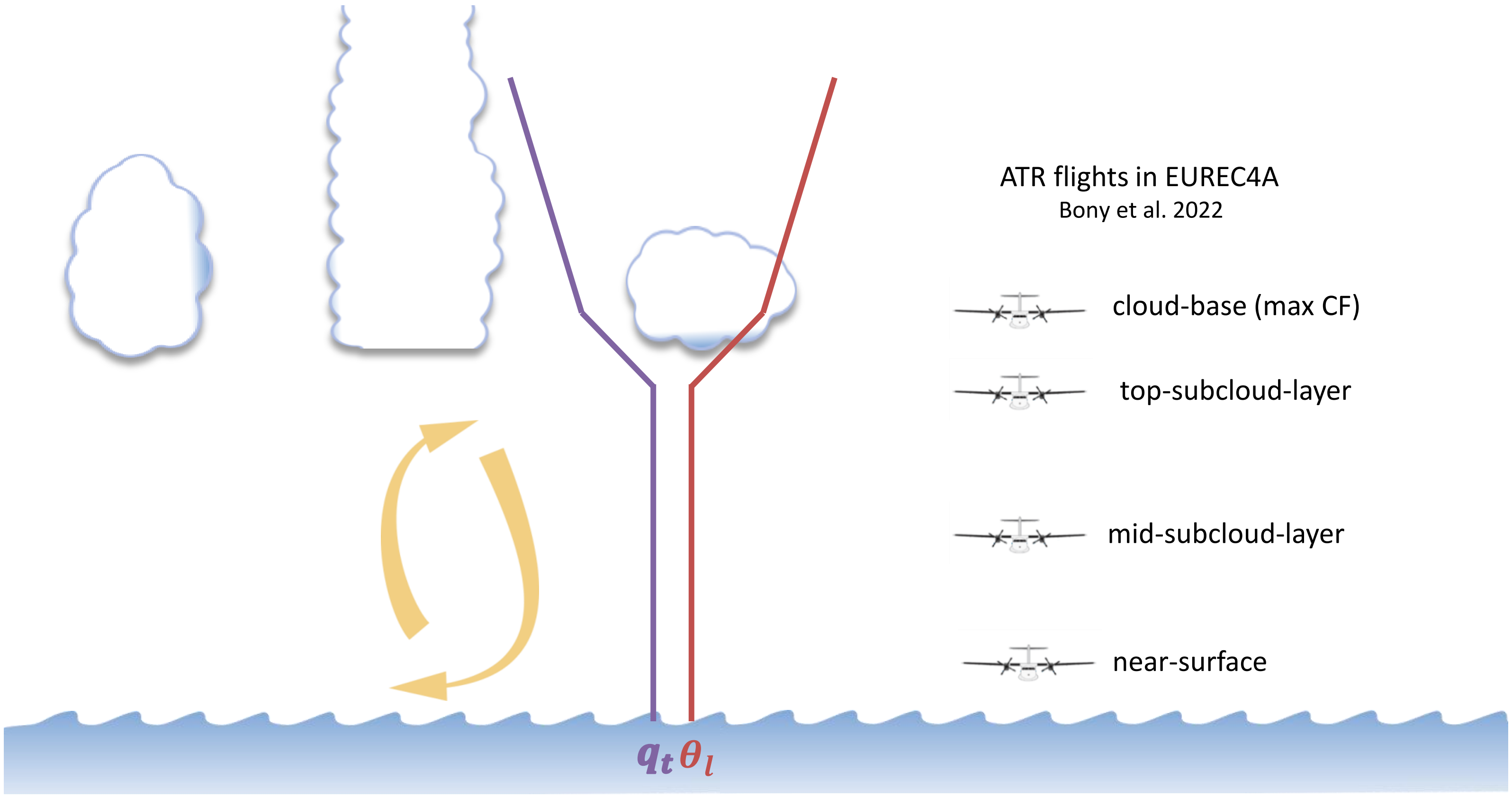
Jan-Feb 2020 in western Atlantic

4 manned aircrafts + 3 autonomous vehicles
4 research vessels + many drifters/buoys
1 ground-based station BCO

including French SAFIRE ATR-42 (19 flights x 4 h)

Stevens et al. 2021, Bony et al. 2022

EUREC4A: ATR-42 sampling strategy



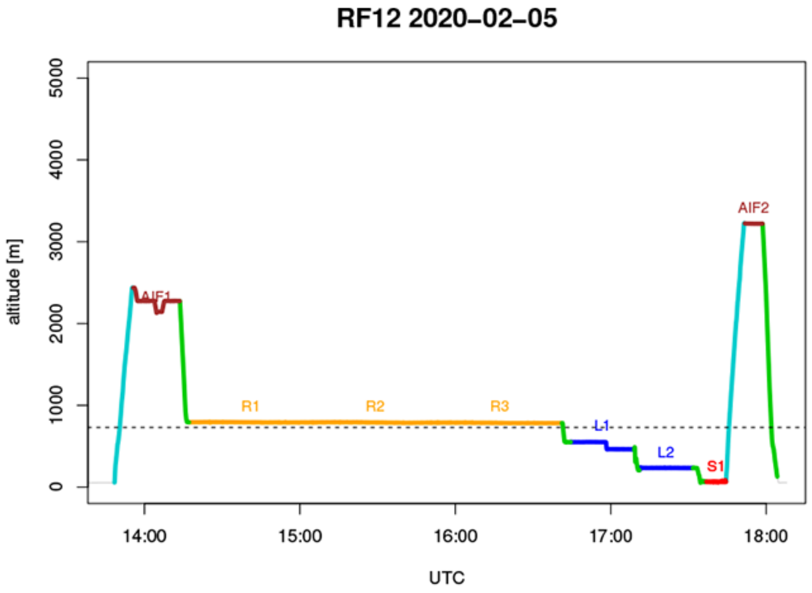
EUREC4A: ATR-42 flight patterns

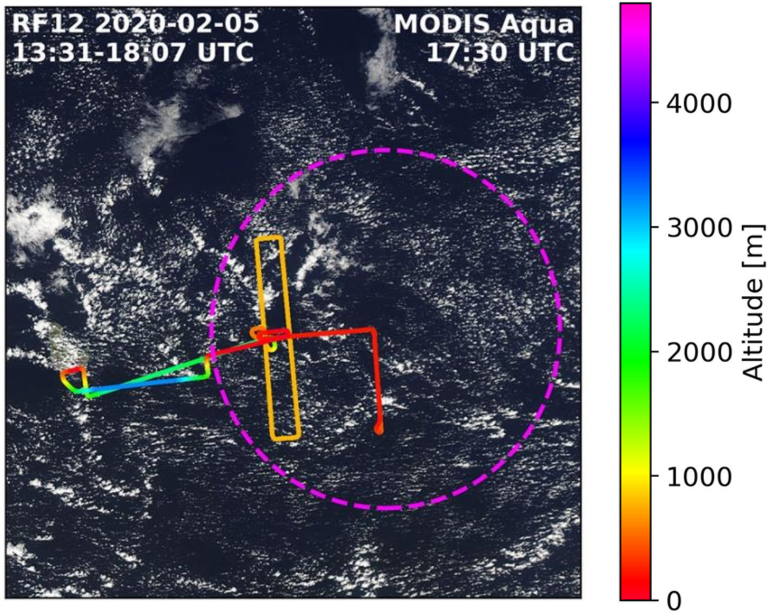
Rectangles 120x20 km perpendicular to the mean easterly wind at **cloud base** (targeted level of max cloud fraction)

L-shape legs 60+60 km, along/across wind, near the **top of the sub-cloud layer**, 150-200 m below cloud base

L-shape legs 60+60 km, along/cross wind, near the **middle of the sub-cloud layer**

Near-surface leg about 40 km at 60 m



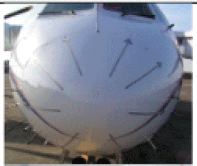


Bony et al. 2022

EUREC4A: ATR-42 selected instruments

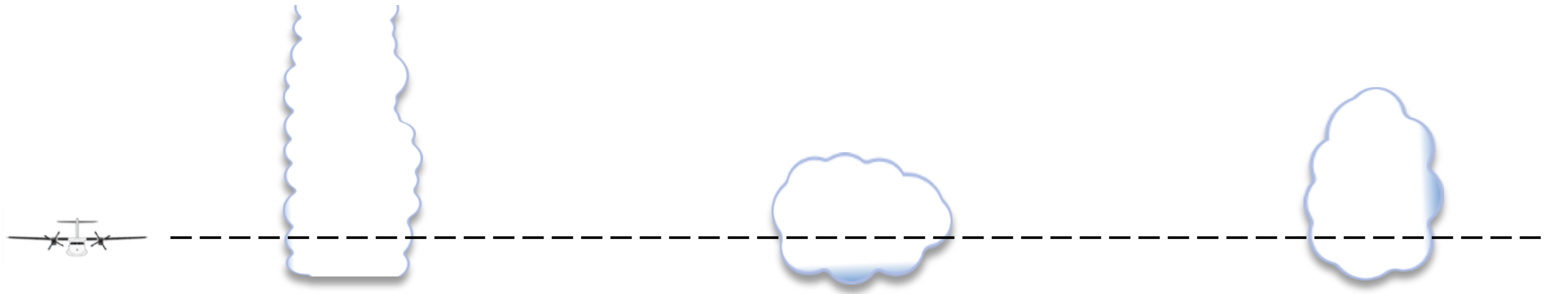
25 Hz

~4 m

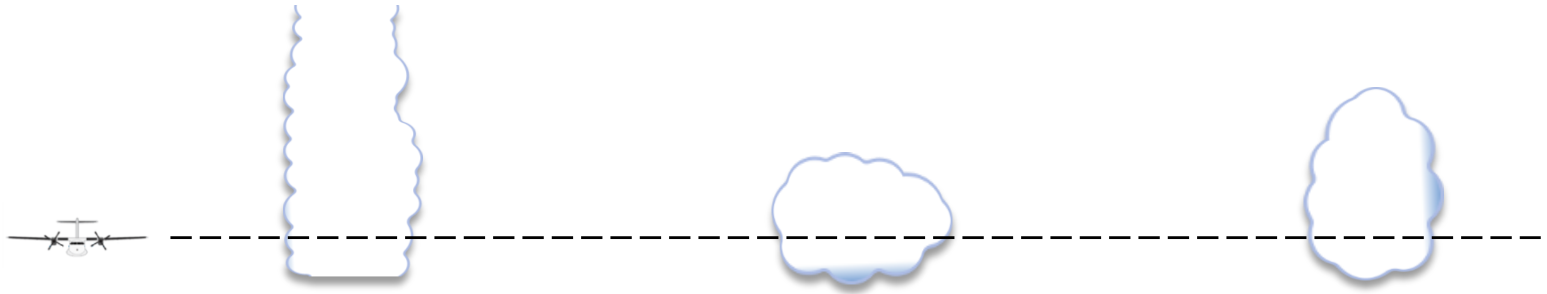
Instrument	Brief description	Position on ATR	
5-hole radome	For measuring the differential pressure around the nose of the aircraft	radome	
Pitot probes	Rosemount and Thales transducers connected to Pitot probes measuring static and dynamic pressure	fuselage	
Rosemount 1	E102AL non-deiced temperature sensor	nose (right-hand side); [N1-4, FR2-3]	
Rosemount 2	E102AL deiced temperature sensor	fuselage (right-hand side); [N1-8, FR15-16]	
Fine wire	fine wire resistance for measuring fast temperature fluctuations	nose (left-hand side); [N1-1, FR2-3]	

Bony et al. 2022

Measurements in cumuli: Cloud detection



Measurements in cumuli: Cloud detection



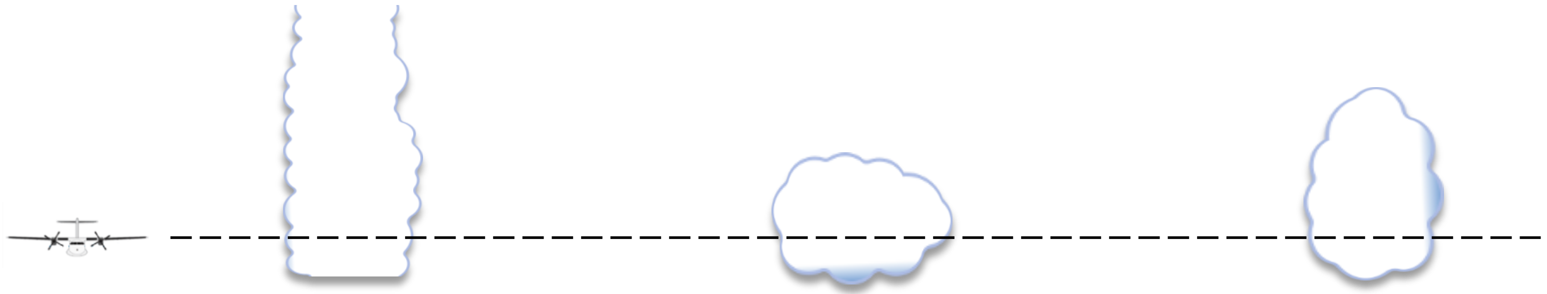
<u>PMA cloud mask</u>

- CDP-2 + 2D-S composite in dataset Coutris (2021)
- $LWC|_{2\ \mu\mathrm{m} < D < 90\ \mu\mathrm{m}} > 0.01\,\frac{\mathrm{g}}{\mathrm{m}^3}$
- available at 1 Hz, i.e. ~100 m resolution

<u>RH cloud mask</u>

- RH calculated following Bony et al. 2022
- $RH > 98\ \%$
- available at 25 Hz, i.e. ~4 m resolution

Measurements in cumuli: Cloud detection



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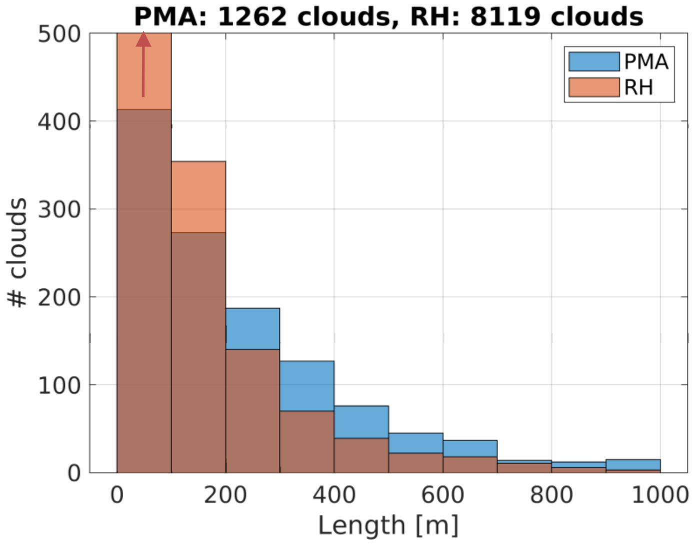
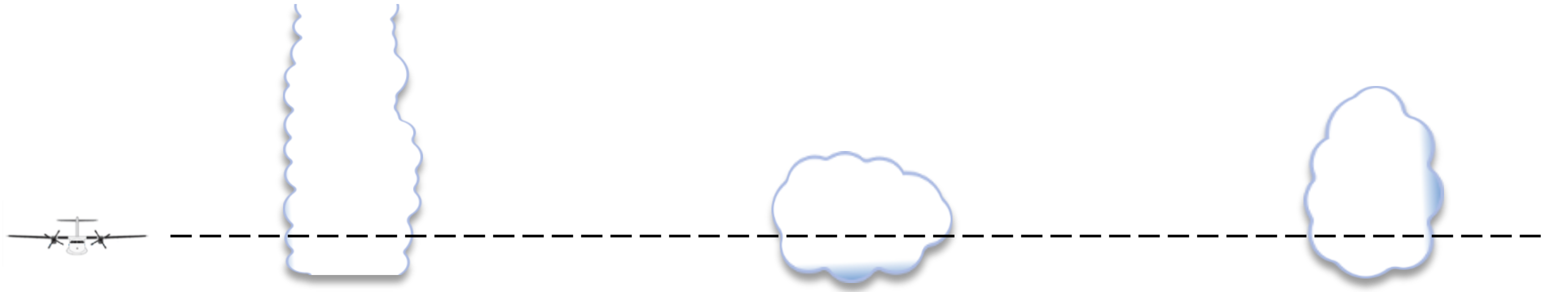
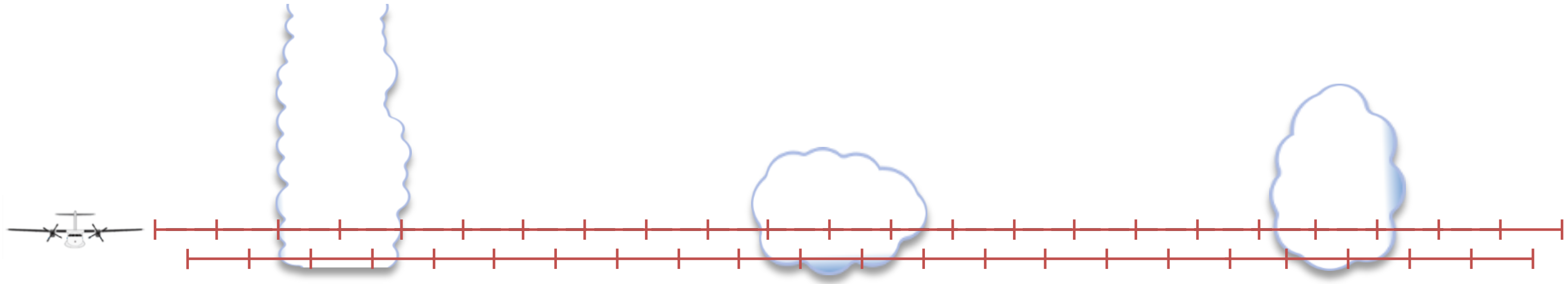


Measurements in cumuli: Conditioning of statistics

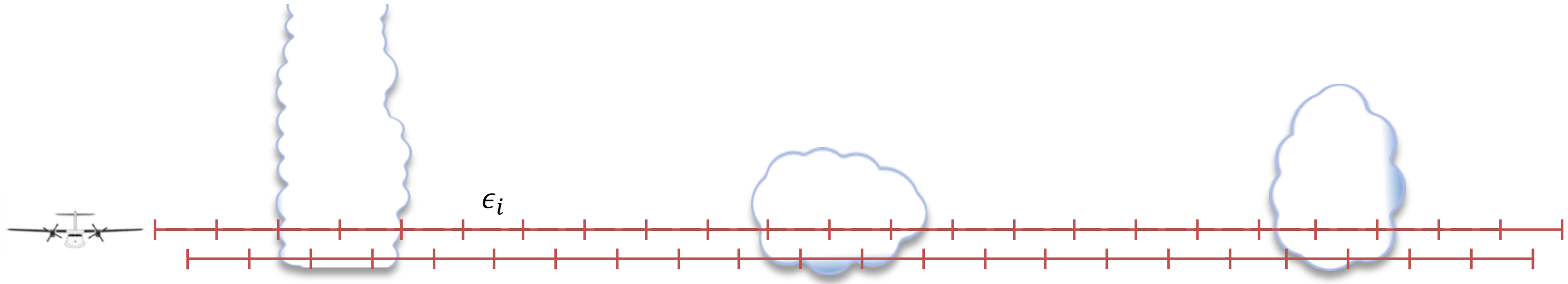


Measurements in cumuli: Conditioning of statistics



Define averaging windows of 200 m overlapping by ½ length.

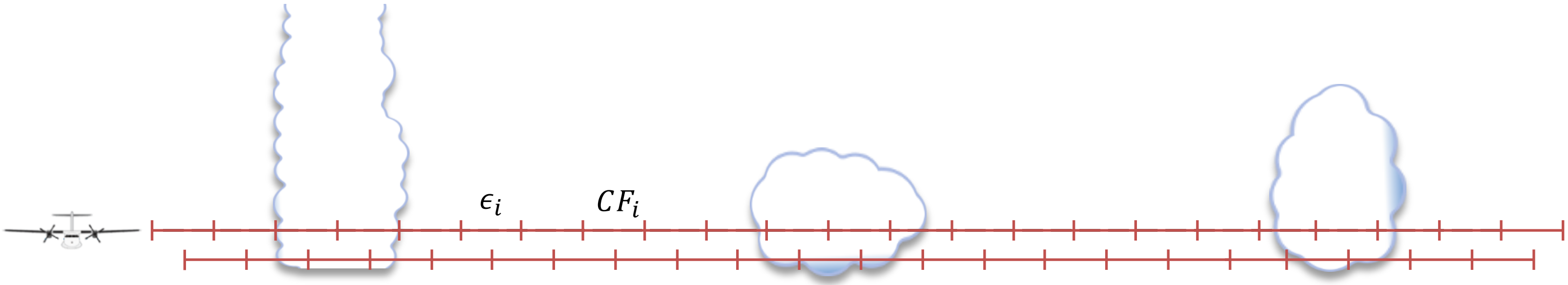
Measurements in cumuli: Conditioning of statistics



Define averaging windows of 200 m overlapping by ½ length.

Estimate turbulence parameters inside those windows.

Measurements in cumuli: Conditioning of statistics

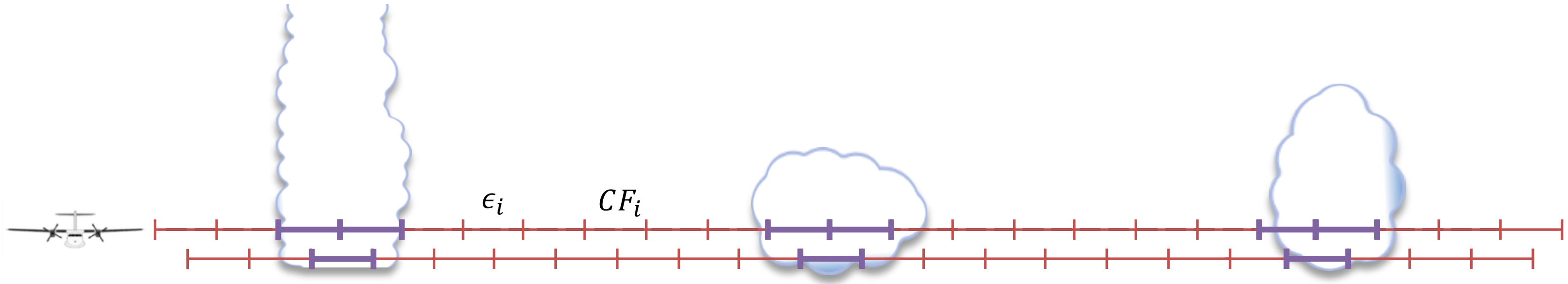


Define averaging windows of 200 m overlapping by ½ length.

Estimate turbulence parameters inside those windows.

Estimate cloud fraction in each window using RH or PMA cloud mask.

Measurements in cumuli: Conditioning of statistics



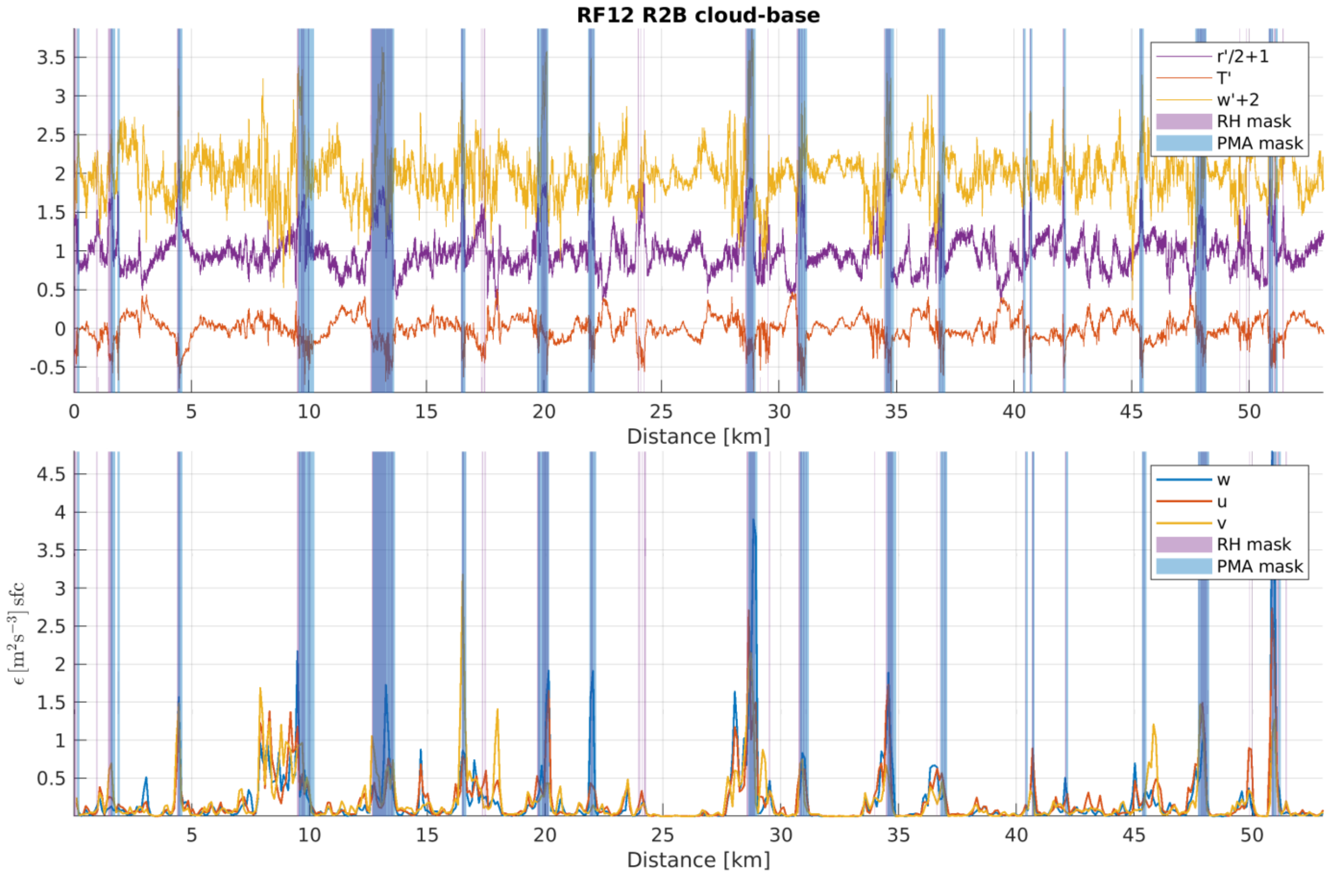
Define averaging windows of 200 m overlapping by ½ length.

Estimate turbulence parameters inside those windows.

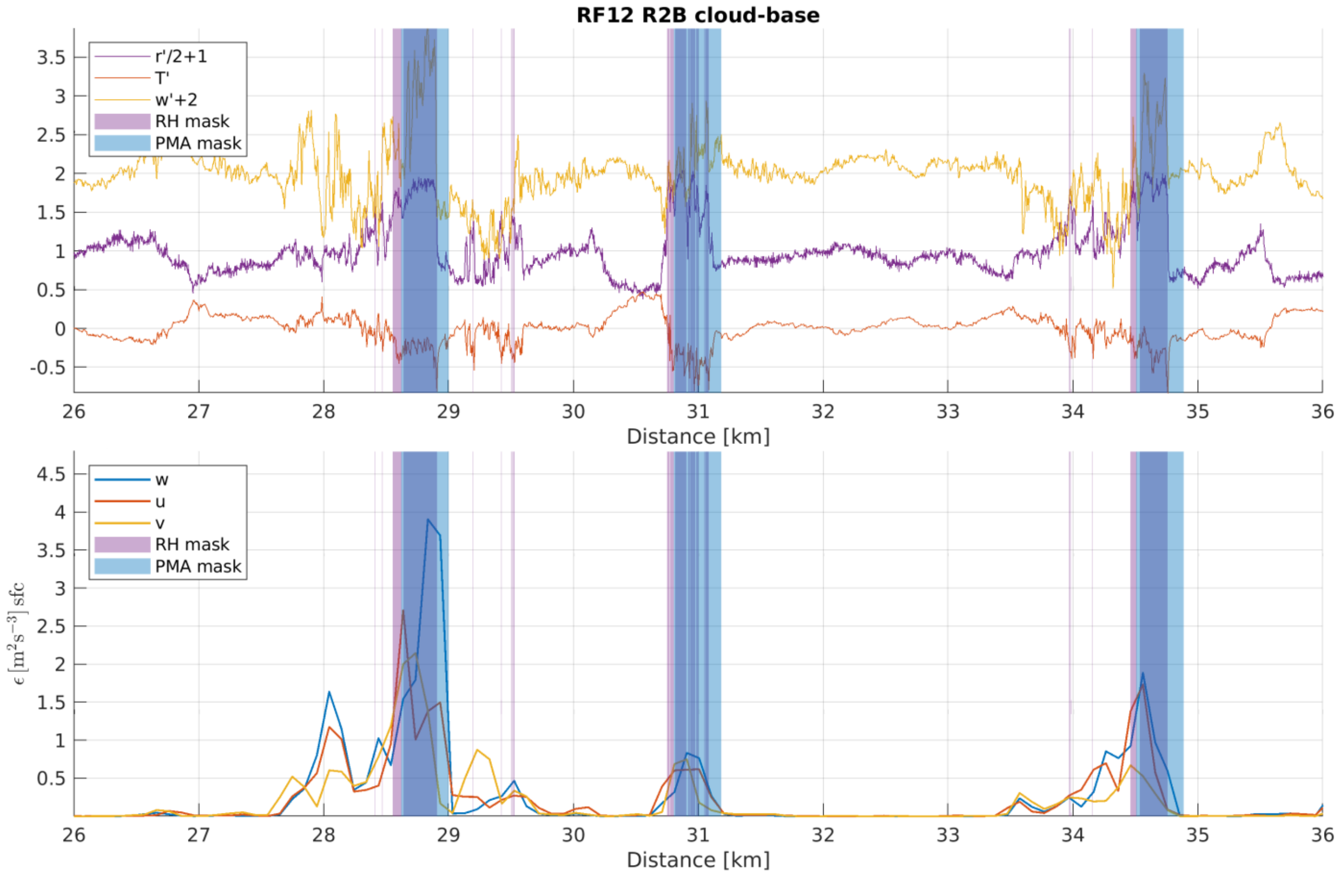
Estimate cloud fraction in each window using RH or PMA cloud mask.

Consider windows with CF>2/3 as cloudy whereas CF=0 as clear-air.

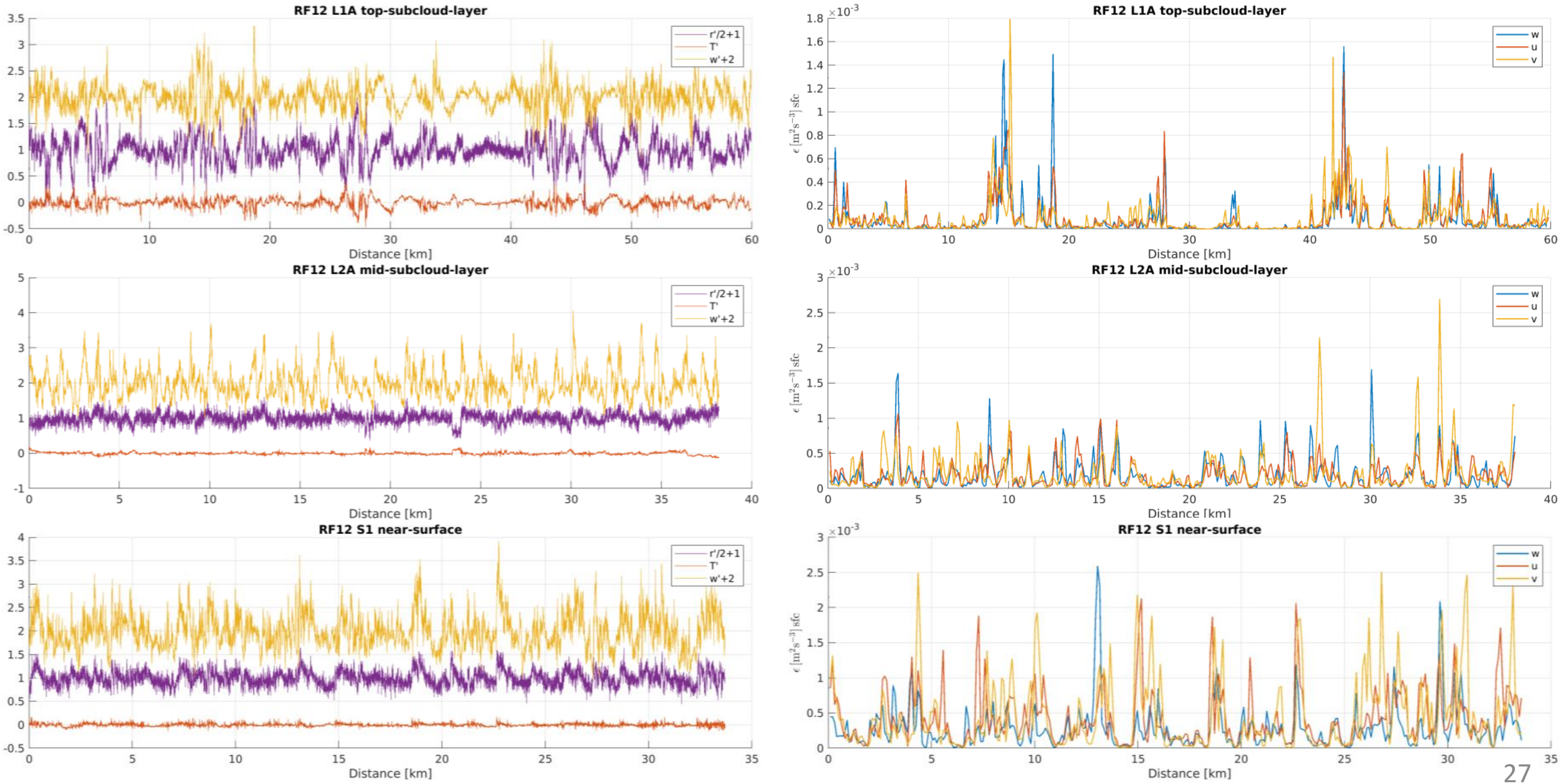
Shallow cumulus BL: Example timeseries at cloud-base



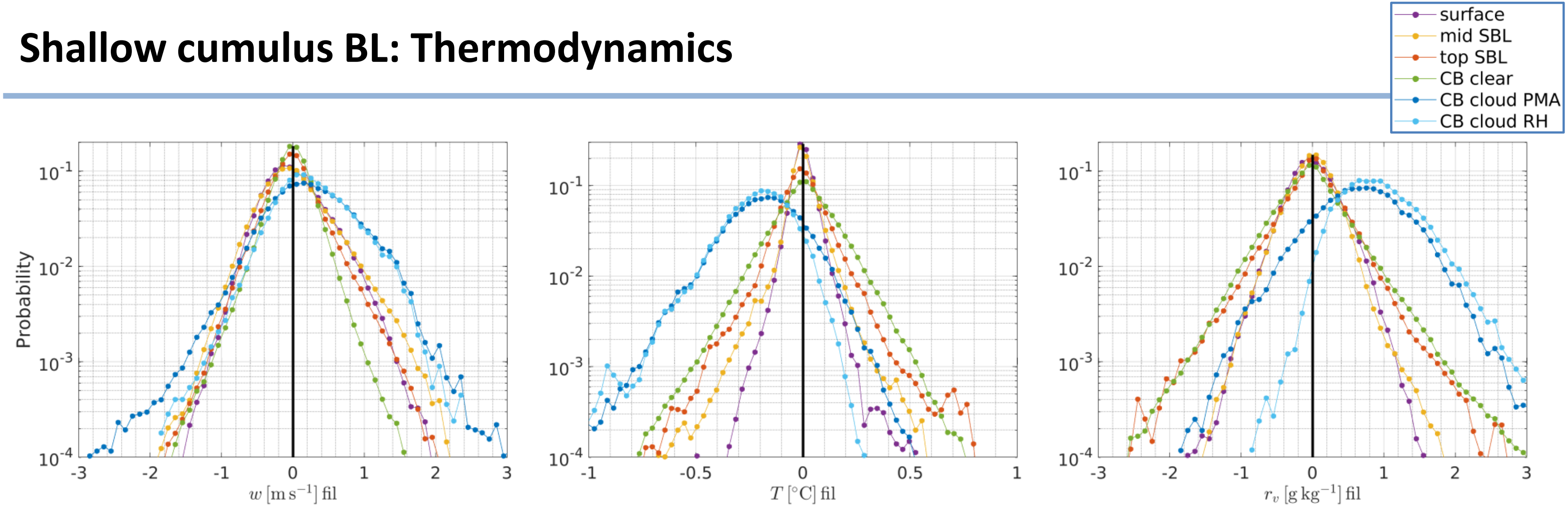
Shallow cumulus BL: Example timeseries at cloud-base (zoom)



Shallow cumulus BL: Example timeseries in the subcloud-layer



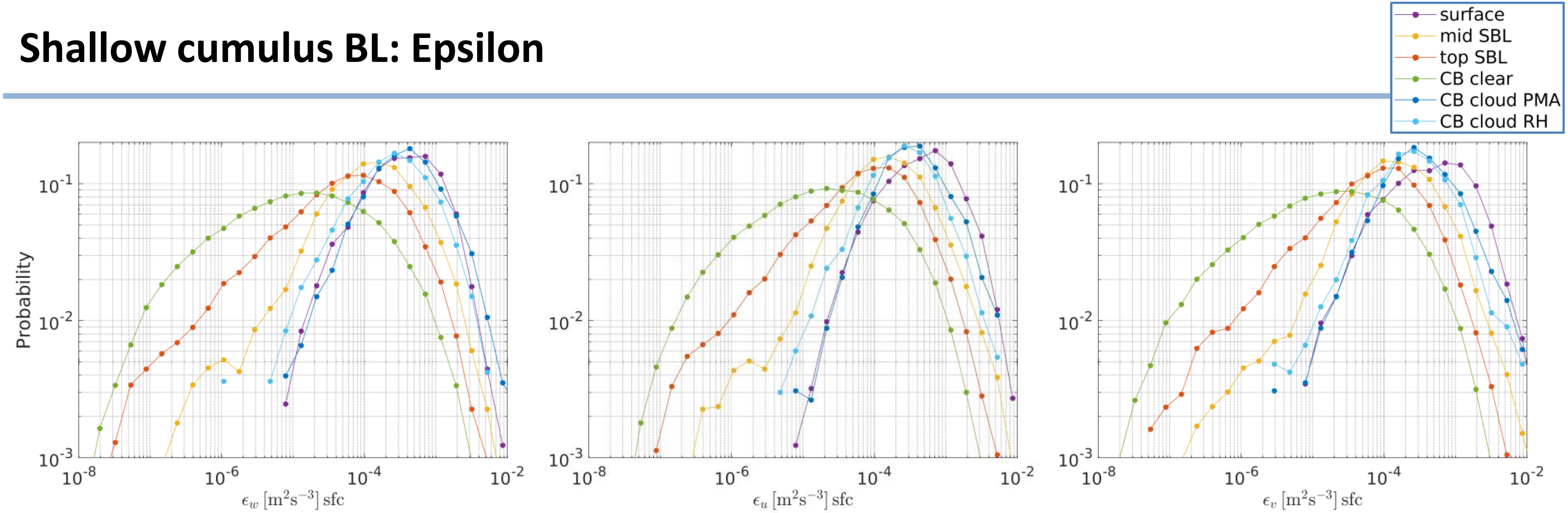
Shallow cumulus BL: Thermodynamics



	CB clear	PMA cloud	RH cloud
w' [m/s]	-0.013 ± 0.280	0.25 ± 0.62	0.28 ± 0.51
T'[℃]	0.009 ± 0.155	-0.18 ± 0.18	-0.21 ± 0.16
r_v' [g/kg]	-0.033 ± 0.533	0.69 ± 0.66	0.95 ± 0.56

mean ± standard deviation

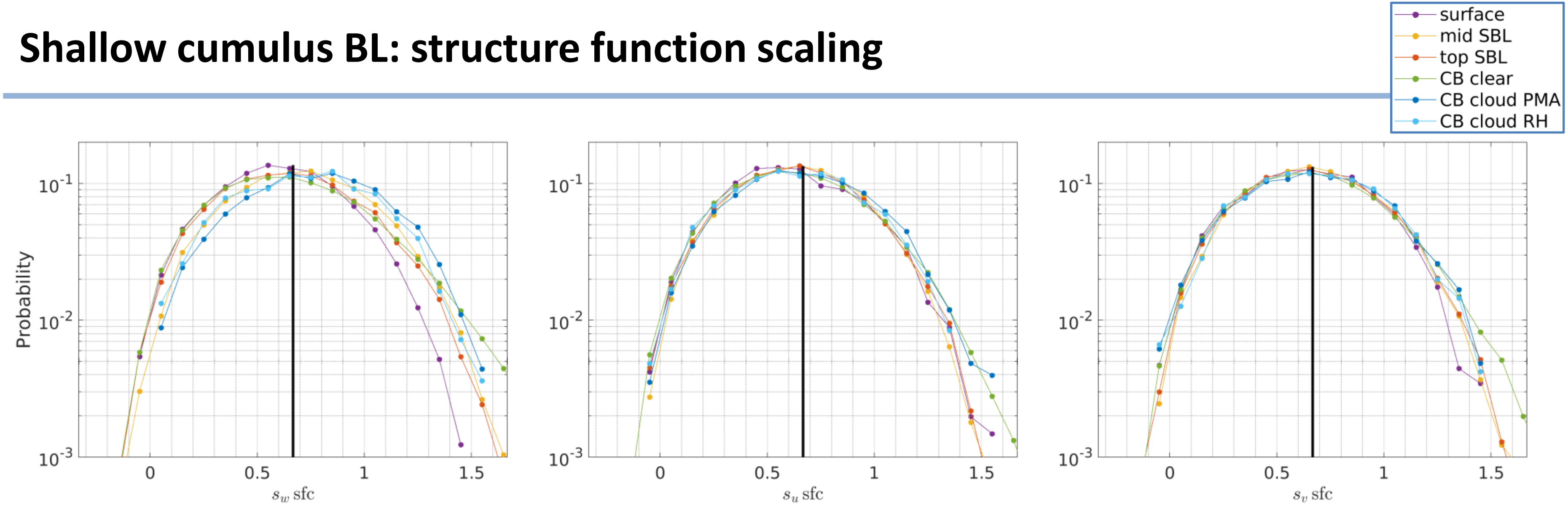
Shallow cumulus BL: Epsilon



$[\mathrm{cm^2 s^{-3}}]$	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
ϵ_w	3.25 ± 3.85	1.12 ± 1.72	0.43 ± 0.85	0.11 ± 0.24	3.35 ± 4.27	2.17 ± 2.99
ϵ_u	4.27 ± 5.04	1.33 ± 1.88	0.62 ± 1.09	0.17 ± 0.35	3.27 ± 3.68	2.33 ± 3.40
ϵ_v	4.11 ± 5.58	1.25 ± 1.87	0.56 ± 1.03	0.15 ± 0.32	2.95 ± 3.76	2.25 ± 3.01

mean ± standard deviation

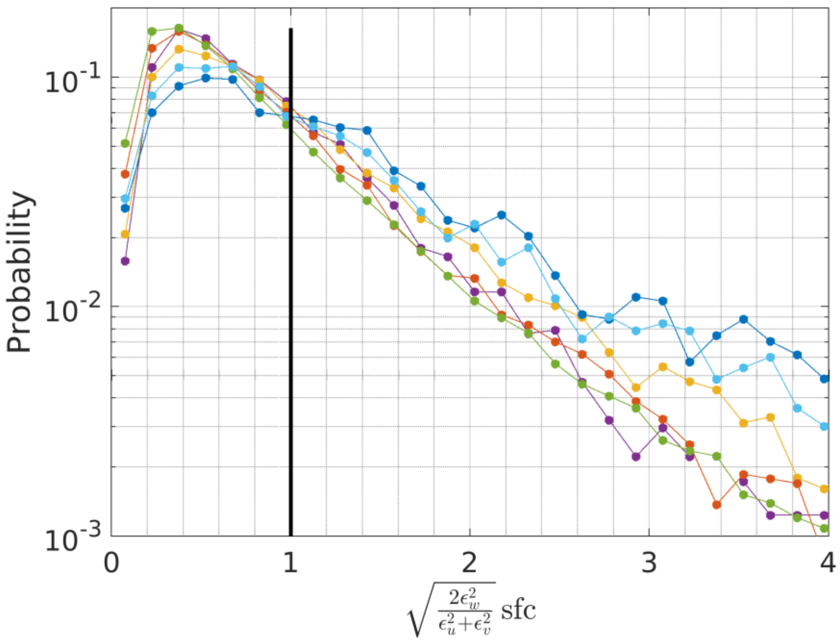
Shallow cumulus BL: structure function scaling



	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
s_w	0.62 ± 0.28	0.71 ± 0.31	0.66 ± 0.31	0.67 ± 0.34	0.77 ± 0.31	0.73 ± 0.31
s_u	0.62 ± 0.29	0.64 ± 0.28	0.64 ± 0.29	0.64 ± 0.31	0.67 ± 0.30	0.64 ± 0.30
s_v	0.64 ± 0.29	0.67 ± 0.29	0.66 ± 0.30	0.67 ± 0.32	0.67 ± 0.31	0.67 ± 0.30

mean ± standard deviation

Shallow cumulus BL: Anisotropy



	surface	mid SBL	top SBL	CB clear	PMA cloud	RH cloud
A_ϵ	0.86 ± 0.67	1.02 ± 0.90	0.86 ± 0.82	0.82 ± 0.94	1.31 ± 1.17	1.15 ± 1.08

mean ± standard deviation

Shallow cumulus BL: Summary